LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

LHCb

Sergey Barsuk, LAL Orsay
sergey.barsuk@lal.in2p3.fr

Charmonium production at LHCb

Selected results

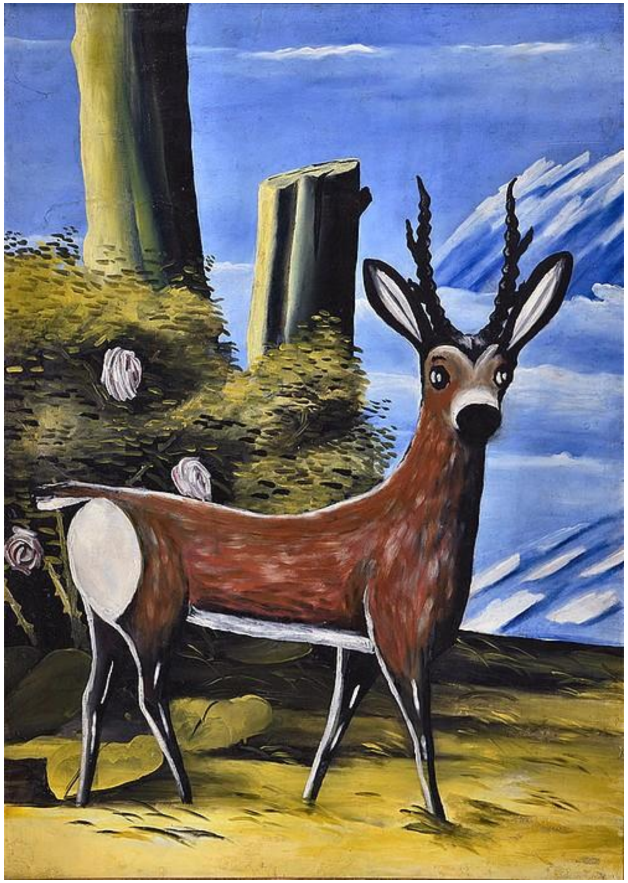
中国科学院大学
University of Chinese Academy of Sciences

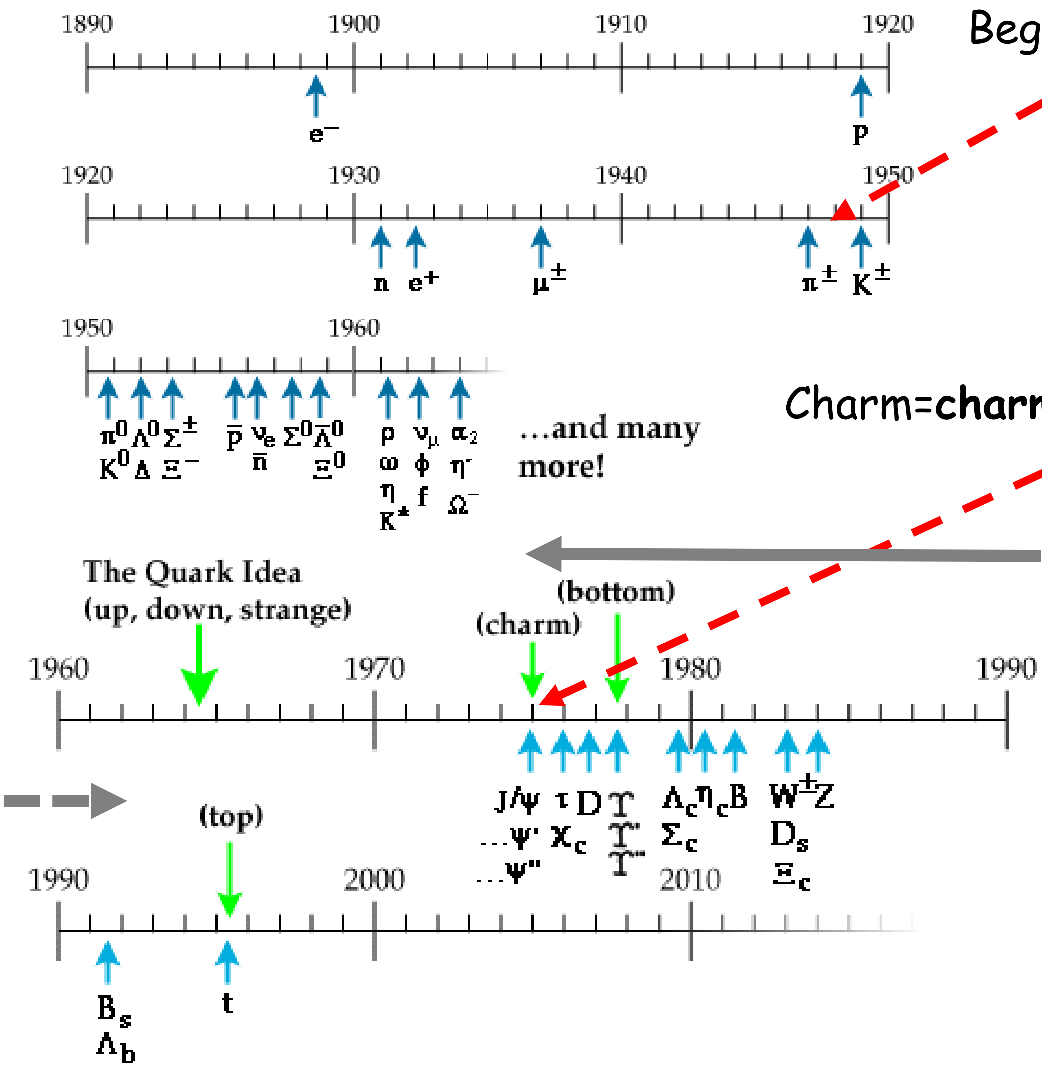
Institute of High Energy Physics
Chinese Academy of Sciences

IHEP/UCAS, 2019年11月8日

Niko Pirosmani

Introduction: charmonium





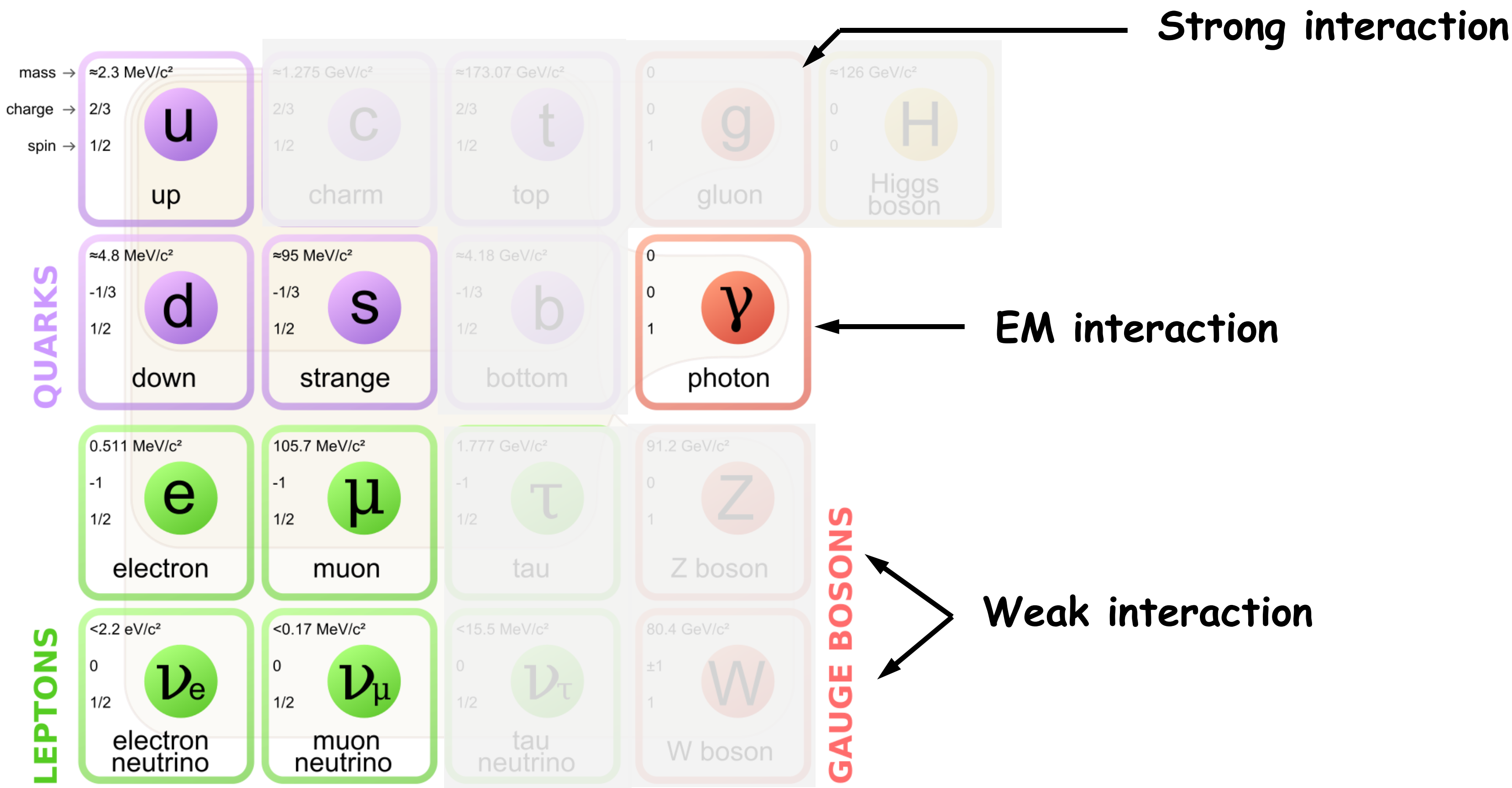
Beginning of flavour physics

Charm=**charmonium** discovery: 1974

Heavy flavours

Heavy flavours

- «Truly » elementary particles : **fermions** (leptons and quarks) and **gauge bosons** … and their **interactions**



Nicola Cabibbo

Nicola Cabibbo: flavour rotation

The quarks d and s involved in weak processes are « rotated » by an angle

θ_c : the Cabibbo angle

$$\begin{pmatrix} u \\ d_c \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix}$$

Couplings : u d $G_F\cos\theta_c$ u s $G_F\sin\theta_c$

Absence of flavor changing neutral current: GIM mechanism

$$u\bar{u} + d\bar{d}\cos^2\theta_c + s\bar{s}\sin^2\theta_c + \boxed{\left(s\bar{d} + \bar{s}d\right)}\cos\theta_c\sin\theta_c$$

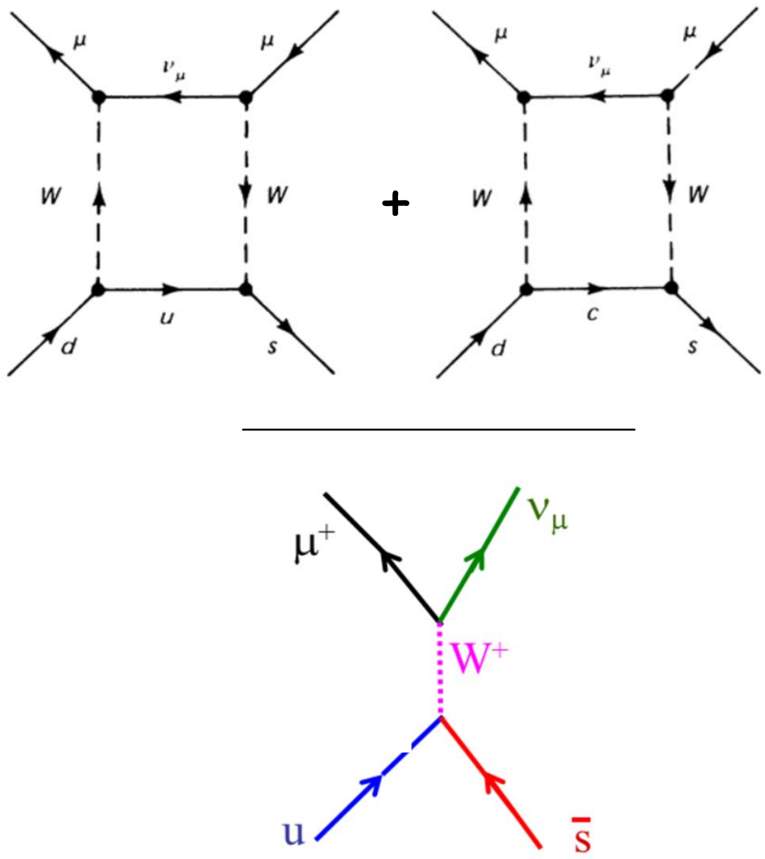
$$\Downarrow$$

$$u\bar{u} + c\bar{c} + \left(d\bar{d} + s\bar{s}\right)\cos^2\theta_c + \left(d\bar{d} + s\bar{s}\right)\sin^2\theta_c = u\bar{u} + c\bar{c} + d\bar{d} + s\bar{s}$$

John Iliopoulos

Sheldon Glashow Luciano Maiani

- Absence of FCNC

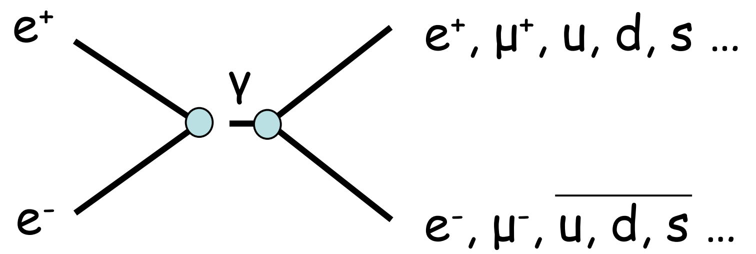


$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

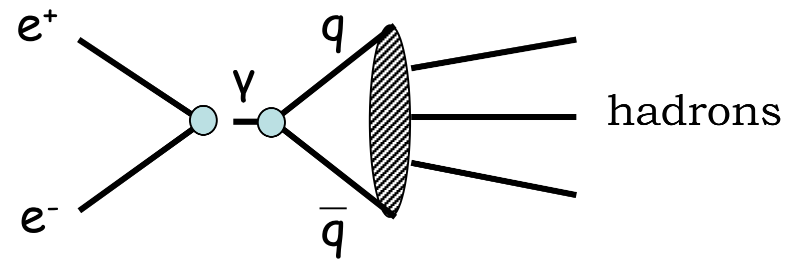
$$\sim (m_c^2 - m_u^2)\cos^2\theta_c \sin^2\theta_c$$

- Prediction of charm quark mass from the contribution to the box diagram: ~1.5 GeV

- Production of pairs of quarks and leptons in e^+e^- collisions



- The $e^+e^- \to q\bar{q}$ detected via decays to stables hadrons

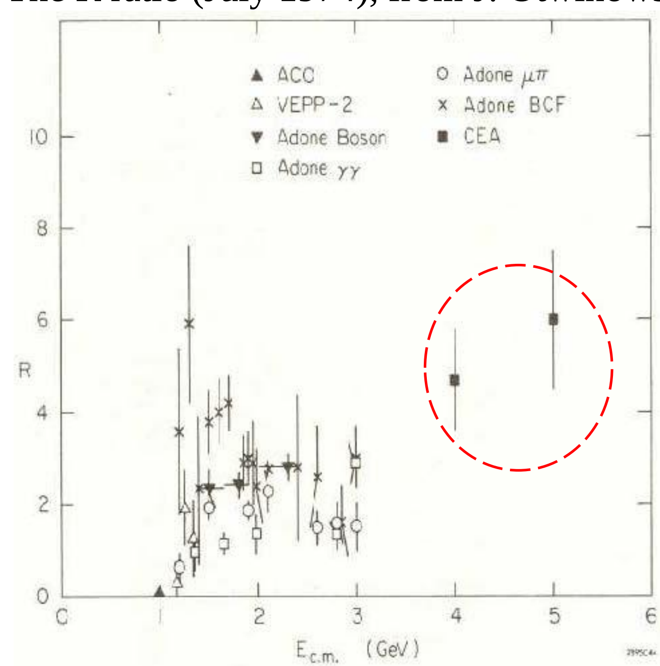


$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_i q_i^2$$

for u,d,s quarks R=2

- Inspiration to measure R ratio at SPEAR/SLAC

The R ratio (July 1974), from J. Otwinowski

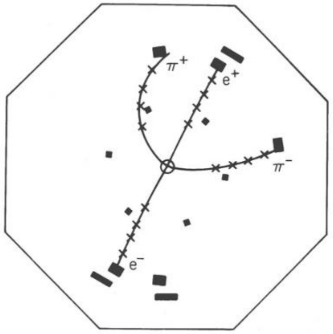


J.J. Augustin et al., PRL 33 (1974) 1406

J.J. Auber et al., PRL 33 (1974) 1404

Burton Richter

- **ψ at SLAC**



Computer reconstruction of a ψ' decay in the Mark I detector

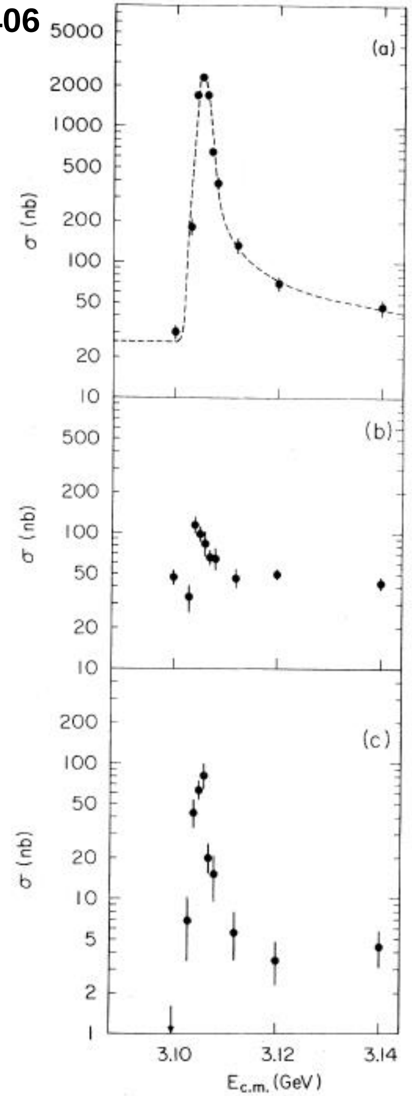


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

- **J at BNL**

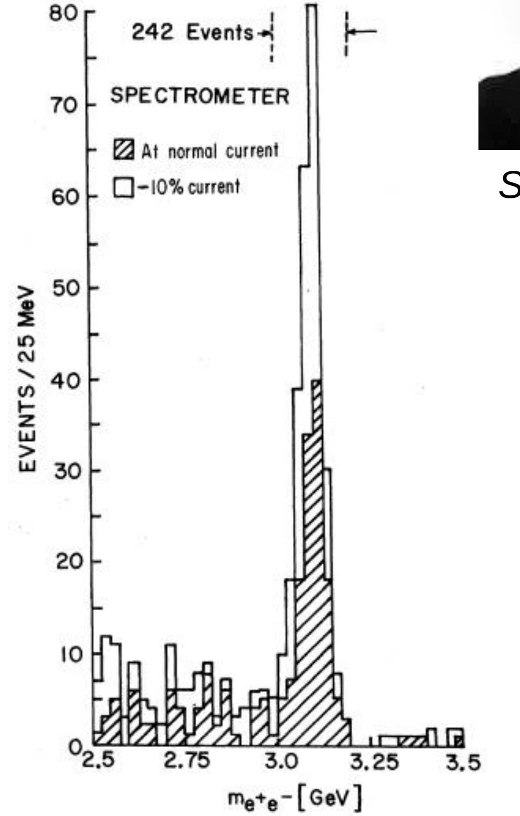
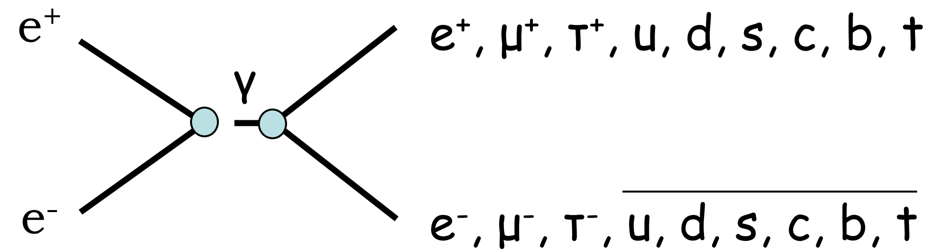


FIG. 2. Mass spectrum showing the existence of *J*. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

Samuel Ting

$J/\psi = c\bar{c}$

Number of players via e^+e^- cross-section

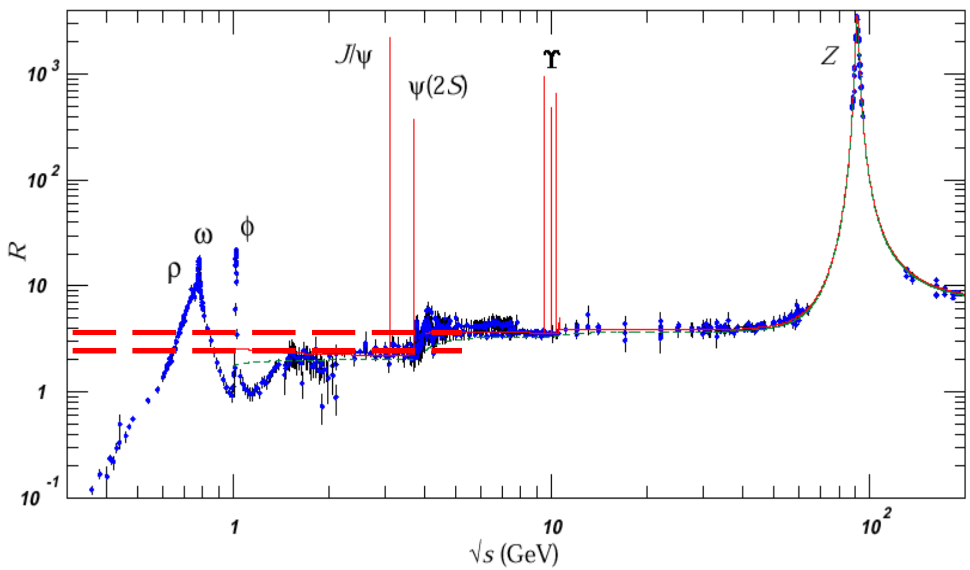


$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_i q_i^2$$

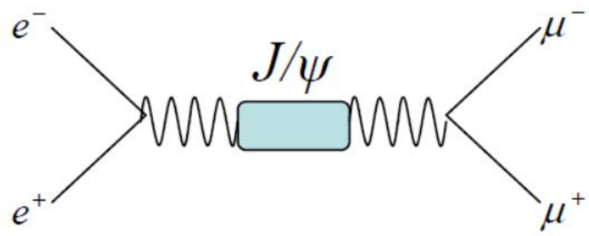
- Guess on **the charge**
- Guess on **the mass**
- With u,d,s R = Nc x [6/9]
- With u,d,s,c R = Nc x [6/9 + q_c^2]

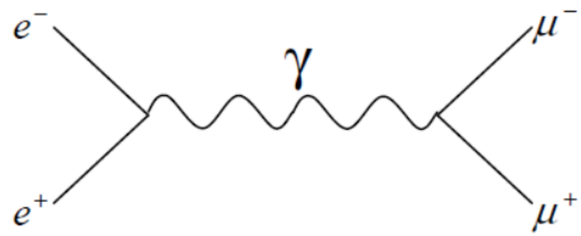
Nc = 3 – number of QCD colours

q_c = + 2/3 ; ($c\bar{c}$) state "J/ψ" of ~3.1 GeV

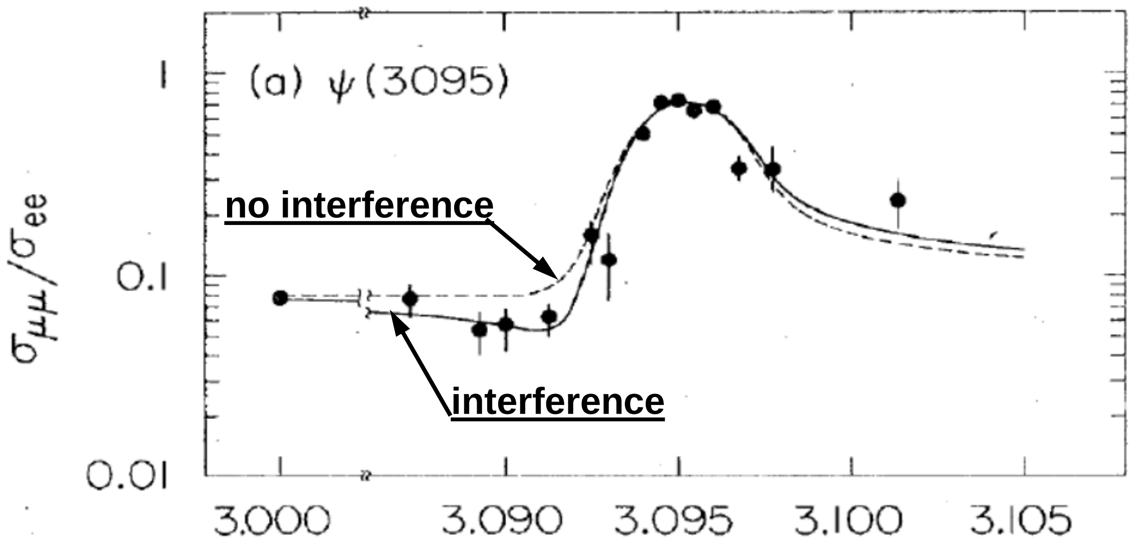


- Two processes contributing to $e^+e^- \rightarrow \mu^+\mu^-$





- If interference, then the same quantum numbers



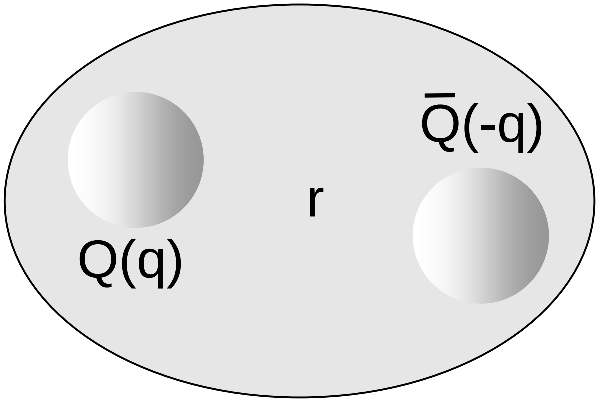
- **J/ψ has $J^{PC} = 1^{--}$ as the photon → privilege at production and at decay !**

$Q\bar{Q}$ potential

- Potential energy of the $Q\bar{Q}$ system (Cornell potential):

$$V(r) = -\frac{\alpha_{eff}}{r} + \sigma r$$

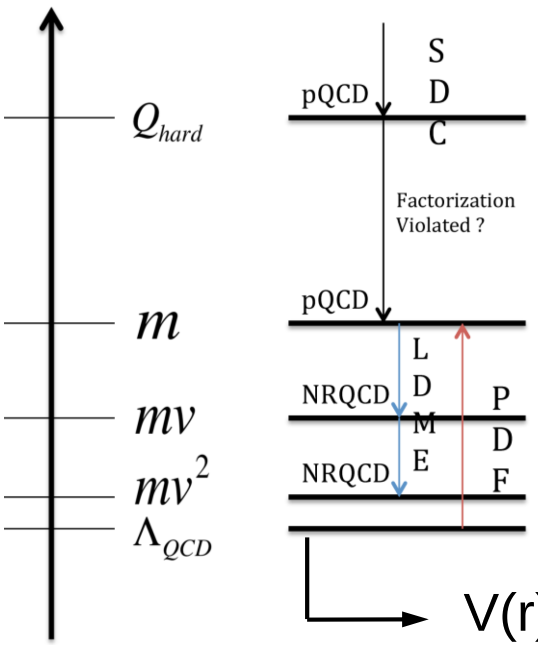
short distance (colour potential) — **long distance** (confinement)



- Perturbative QCD relates $Q\bar{Q}$ potential to scattering amplitude via 1-gluon exchange
- Relates colour charge q and QCD coupling g

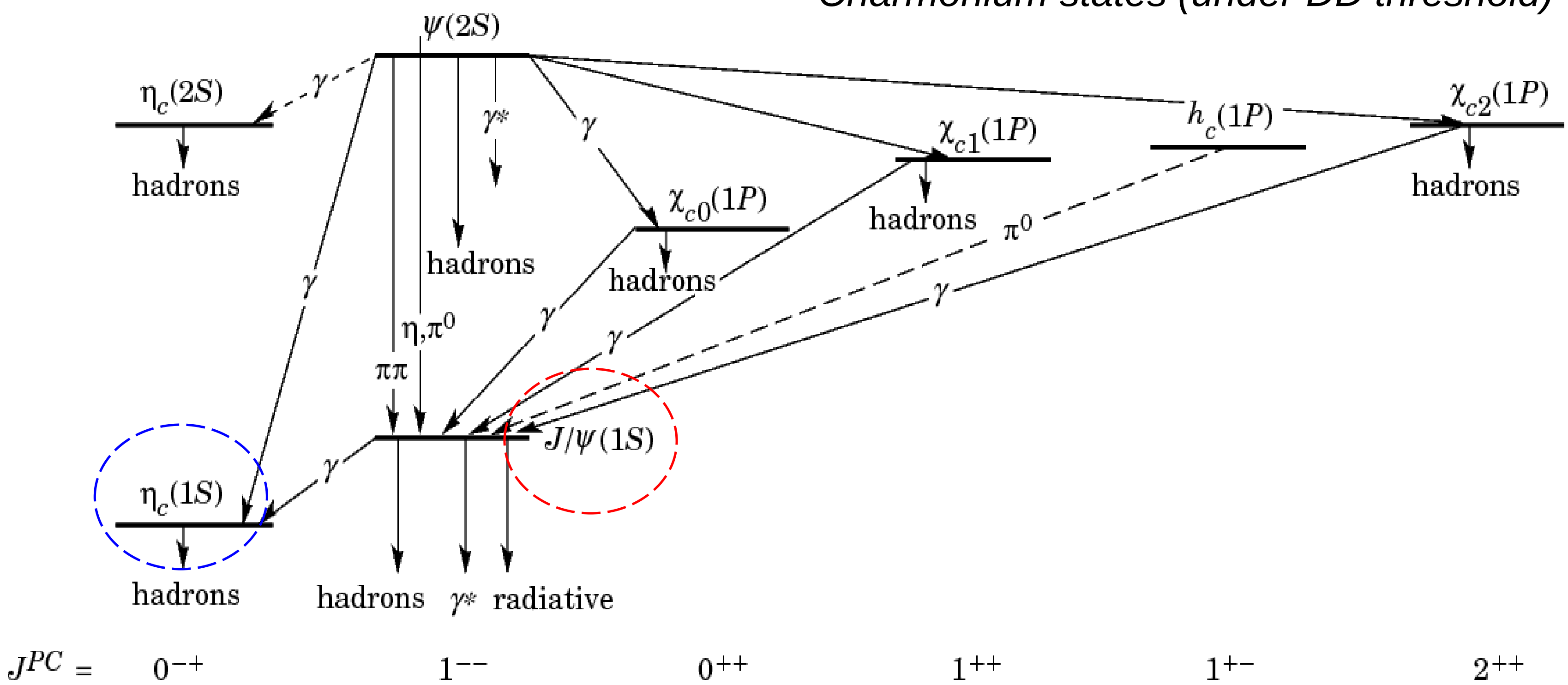
$$q^2 = 4/3\ g^2 = 4/3\ 4\pi\alpha_s$$

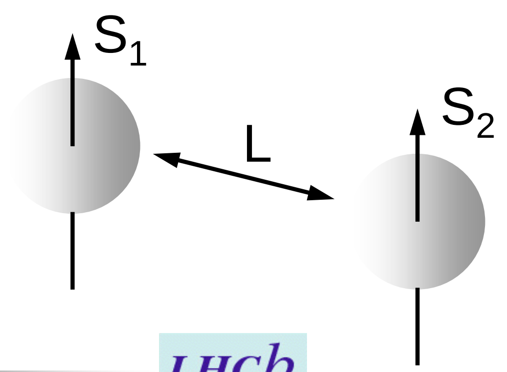
- Can be derived from QCD, but difficult since multi-scale process
- Spectroscopy predictable via set of parameters: m_Q, α_{eff}, σ



$$V(r) = -\frac{\alpha}{r} + \sigma r$$

Charmonium states (under $D\bar{D}$ threshold)





$S = S_1 + S_2$

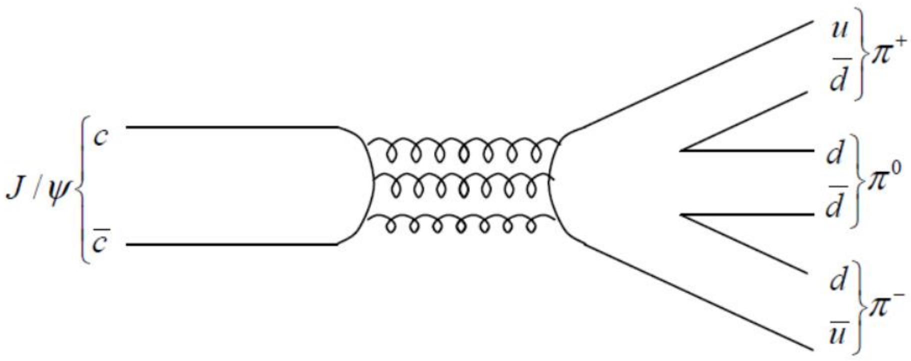
$J = L + S$

$P = (-1)^{L+1}$

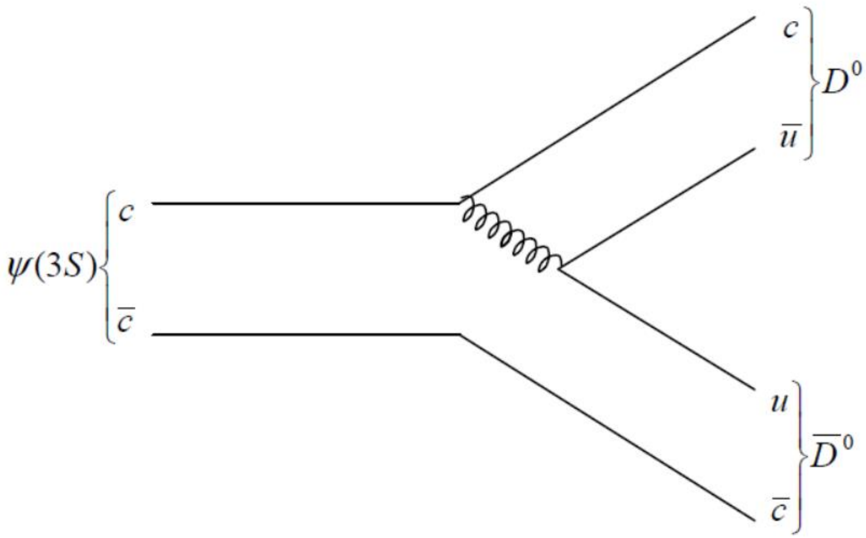
$C = (-1)^{L+S}$

- Hadronic final states give the only possibility to simultaneously reconstruct all known charmonia

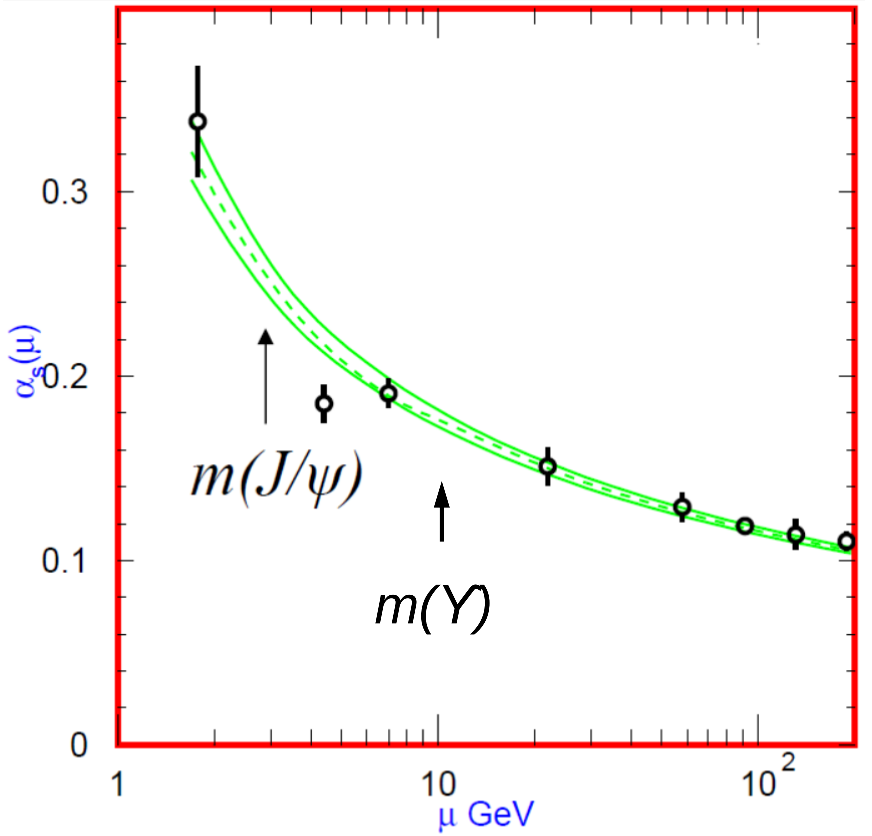
- Below D$\overline{\text{D}}$ threshold: **strong annihilation to two or three gluons** depending on quantum numbers
- The $\alpha_S{}^4$ or $\alpha_S{}^6$ dependence



- Above D$\overline{\text{D}}$ threshold: **decays to D$\overline{\text{D}}$ via single gluon radiation**
- The $\alpha_S{}^2$ dependence



- The α_S rapidly varies with momentum transfer μ of the interaction
- **Coupling** is much **stronger for μ ~ m(u,d) than for μ ~ m(J/ψ)**



- Charmonium production provides **powerful tests** of **QCD-based models**
- First clash to describe **« J/ψ production puzzle »**
- **« J/ψ production AND polarization puzzle »** boosted the progress
- Recently with the $\eta_c(1S)$ production measurement by LHCb more challenging

« J/ψ production AND polarization AND $\eta_c(1S)$ production puzzle »

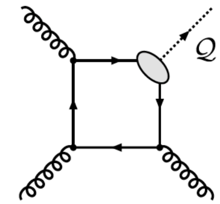
- **Today more precision** in conventional studies and **new sources of input**:

associated production, isolation, production in pPb and PbPb collisions, …

J/ψ hadroproduction puzzle

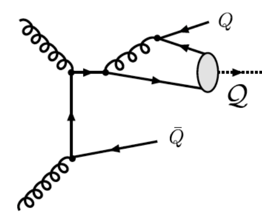
- Comparison of direct p_T differential J/ψ production cross-section measured by CDF with Color Singlet LO (most natural) process.
- Fails both in shape and magnitude.

R. BAIER and R. RUECKL, Z. Phys C 19 (1983), 251



$$a_S^3 \frac{(2m_Q)^4}{p_T^8}$$

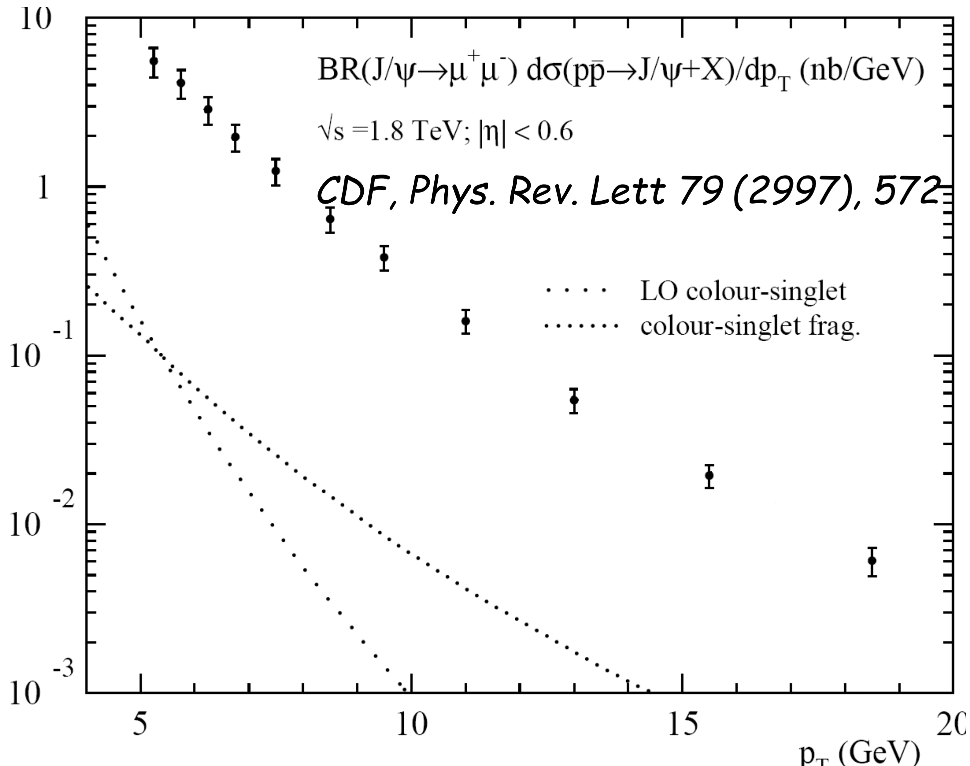
+



$$a_S^4 \frac{1}{p_T^4}$$

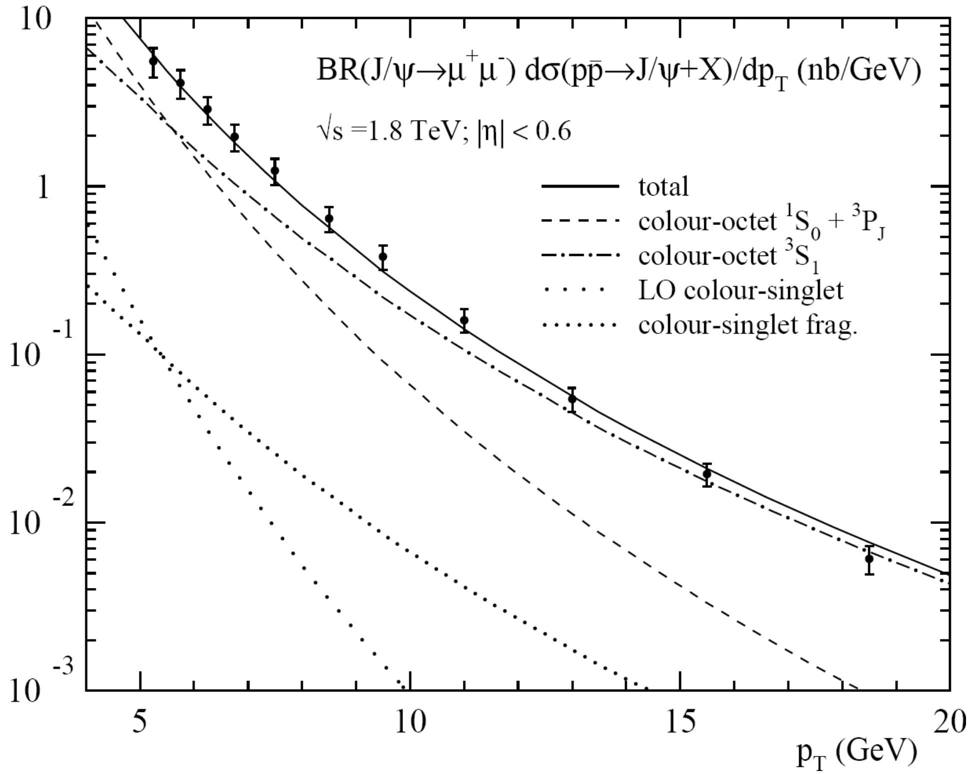
- Add gluon and quark fragmentation (NLO Color Singlet processes)
- Better shape but magnitude is factor 30 too low.

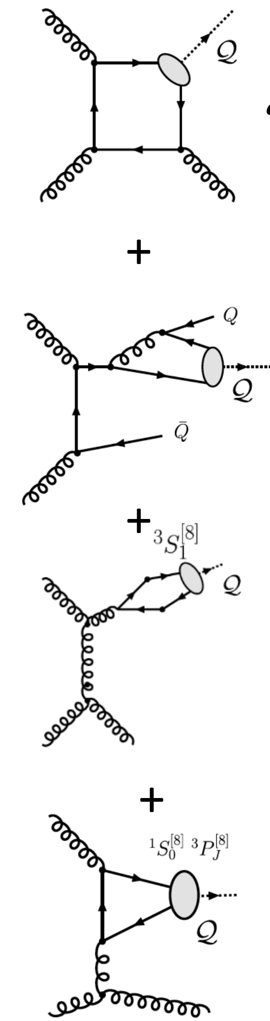
E. BRAATEN, M. A. DONCHESKI, S. FLEMING and M. L. MANGANO, PLB 333 (1994), 548



- Add LO Color-Octet processes from NRQCD
- LDME fitted on the same data

P. L. CHO and A. K. LEIBOVICH, PRD 53 (1996) 150





$a_S^3 \frac{(2m_Q)^4}{p_T^8}$

$a_S^4 \frac{1}{p_T^4}$

$a_S^3 \frac{1}{p_T^4}$

$a_S^3 \frac{1}{p_T^6}$

- Excellent agreement when summing all contributions, with Color-Octet terms being dominant

- Two scales of production:
  hard process of $Q\bar{Q}$ **formation** and **hadronization of** $Q\bar{Q}$ at softer scales
- **Factorization**:

$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle \mathcal{O}^H(n) \rangle$$

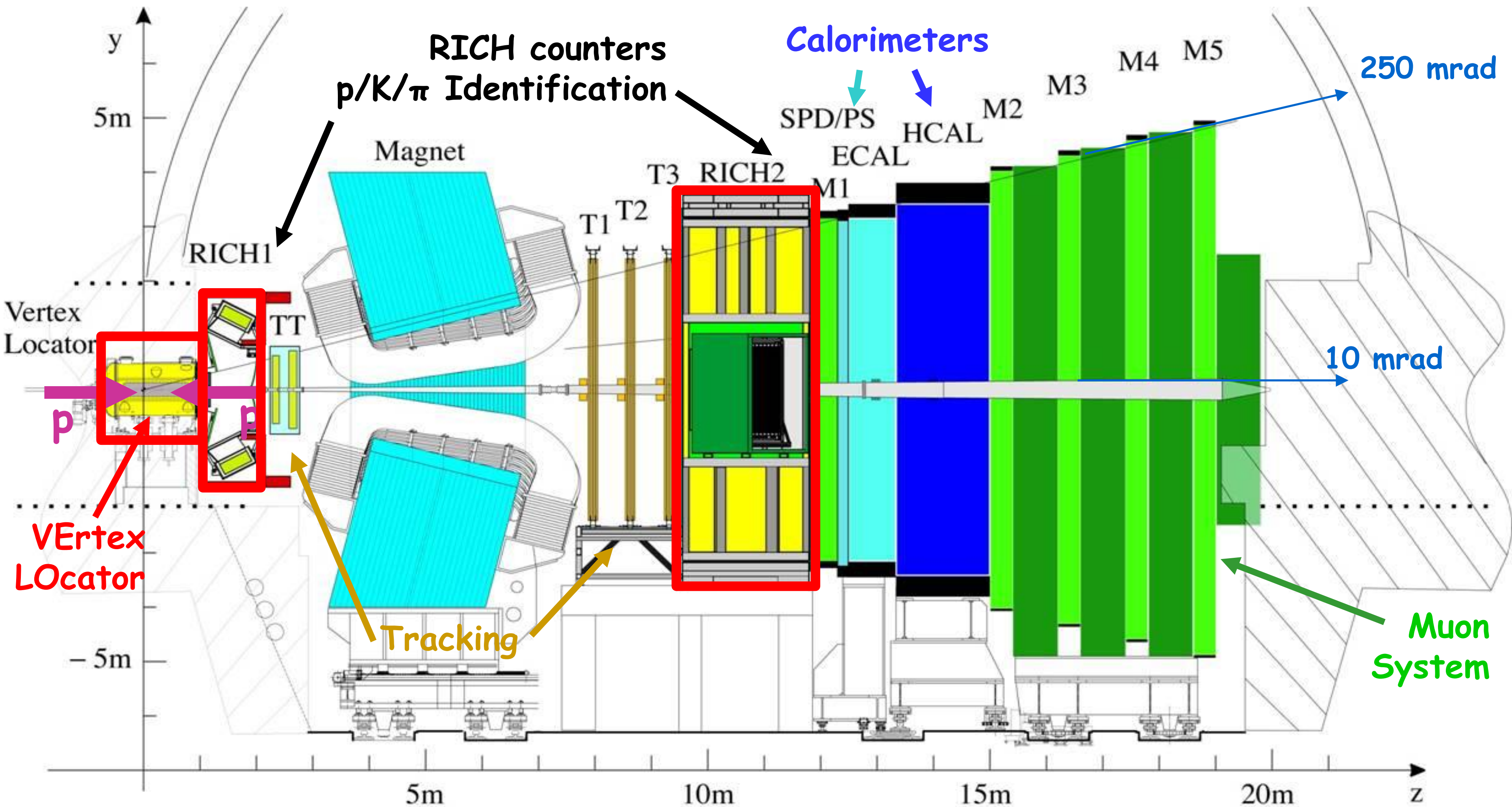
Short distance: perturbative cross-sections + pdf for the production of a $Q\bar{Q}$ pair

Long distance matrix elements (LDME), non-perturbative part

- Colour-singlet model: intermediate $Q\bar{Q}$ state is colourless and has the same J^{PC} quantum numbers as the final-state quarkonium
- NRQCD: all viable colours and J^{PC} allowed for the intermediate $Q\bar{Q}$ state, they are adjusted in the long-distance part with a given probability.
  Long-Distance Matrix Elements (LDME) from experimental data
- **Universality**: *same LDME for prompt production and production in b-decays*
- Heavy-Quark **Spin-Symmetry** (HQSS): links between colour-singlet (CS) and colour-octet (CO) LDME of different quarkonium states

Introduction: LHCb

LHCb – single-arm forward spectrometer



Vertex reconstruction:
VELO

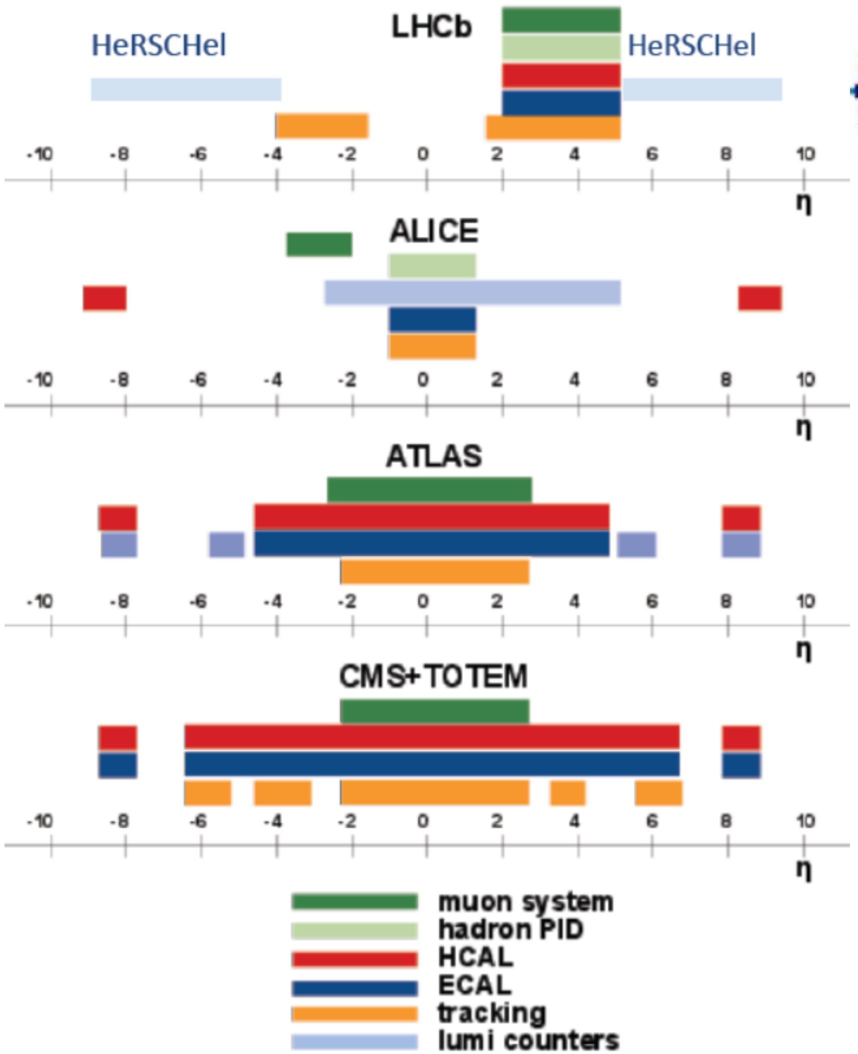
Kinematics:
Magnet
Tracker
Calorimeters

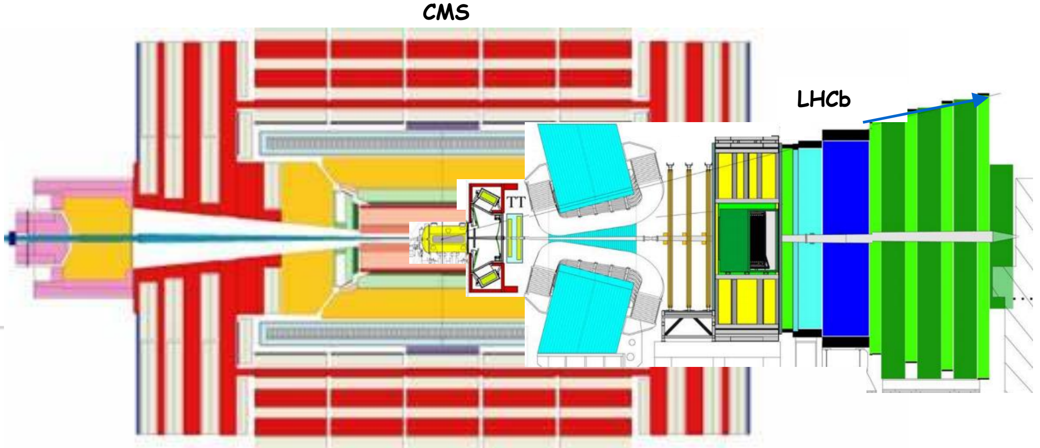
PID:
RICHs
Calorimeters
Muon Chambers

Trigger:
Muon Chambers
Calorimeters
Tracker

- B mesons travel about 1 cm

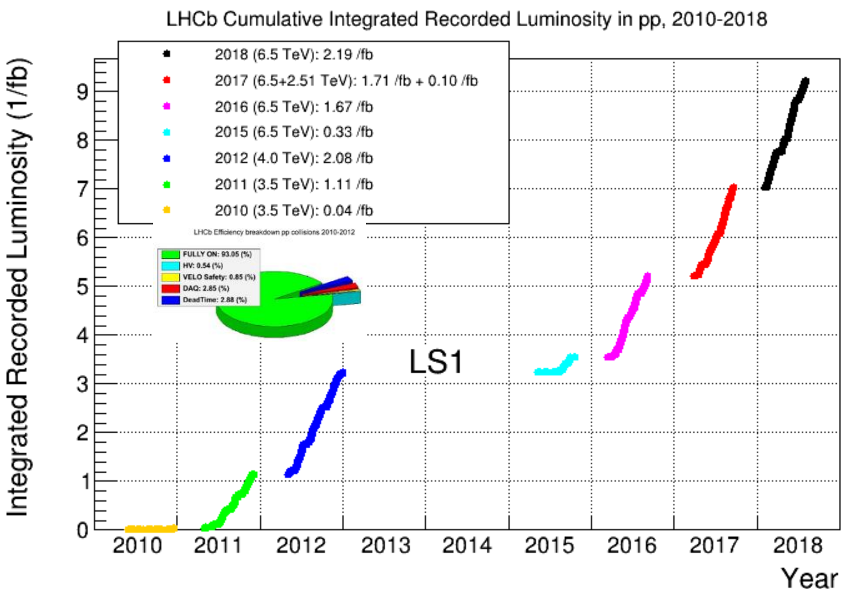
❑ **Complementary cross-section measurements** and overlap in rapidity



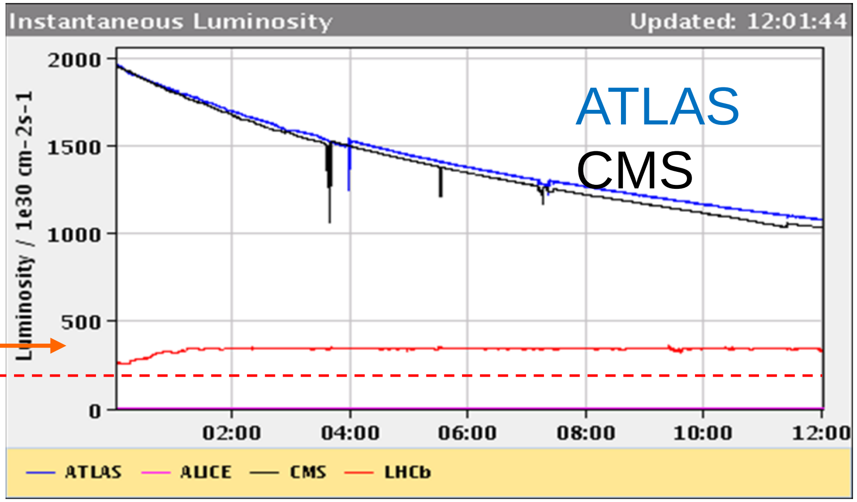


❑ Key detector systems for production measurements: **vertex reconstruction, particle identification (Muon detector, charged hadron ID), Trigger**

- LHCb collected data corresponding to $\int L dt > 9\ fb^{-1}$



- Stable LHCb operation
- Running at up to $L \sim 4 \times 10^{32}\ cm^{-2}s^{-1}$ (higher, than nominal, $2 \times 10^{32}\ cm^{-2}s^{-1}$) in auto-leveling mode



LHCb luminosity levelling

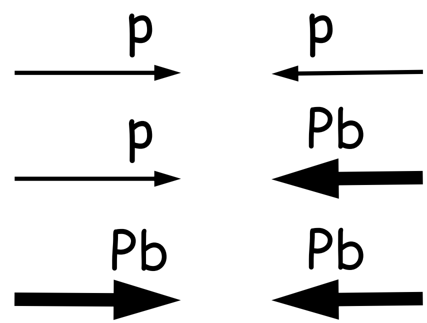
LHCb (design)

- Visual average **number of vertices** is higher, $\mu \sim 1.4$, compared to nominal $\mu = 0.4$
- Higher μ → higher track multiplicity, 1 PV gives 30 tracks/rapidity range, more difficult reconstruction

→ background for D and B decay vertex reconstruction and matching

<min. distance> between 4 PVs ~12 mm, comparable to <B travel distance> ~10 mm

- Collision data at LHCb
  - **pp collisions** $\sqrt{s_{NN}}$ = 7, 8, 13 TeV
  - **pPb collisions** $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV
  - **PbPb collisions** $\sqrt{s_{NN}}$ = 5 TeV
  - Short XeXe run in 2017

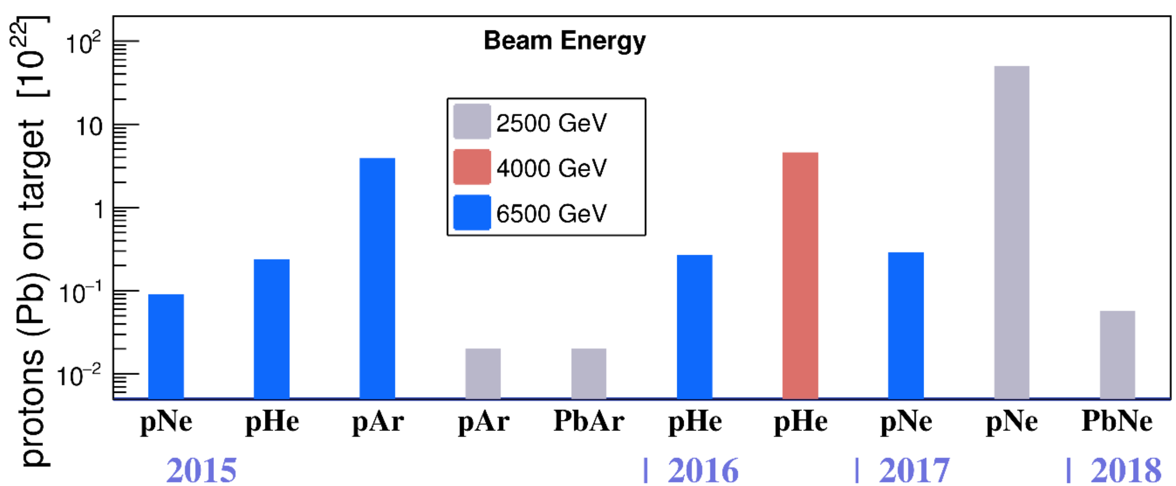


LHCb SMOG: System for Measuring Overlap with Gas

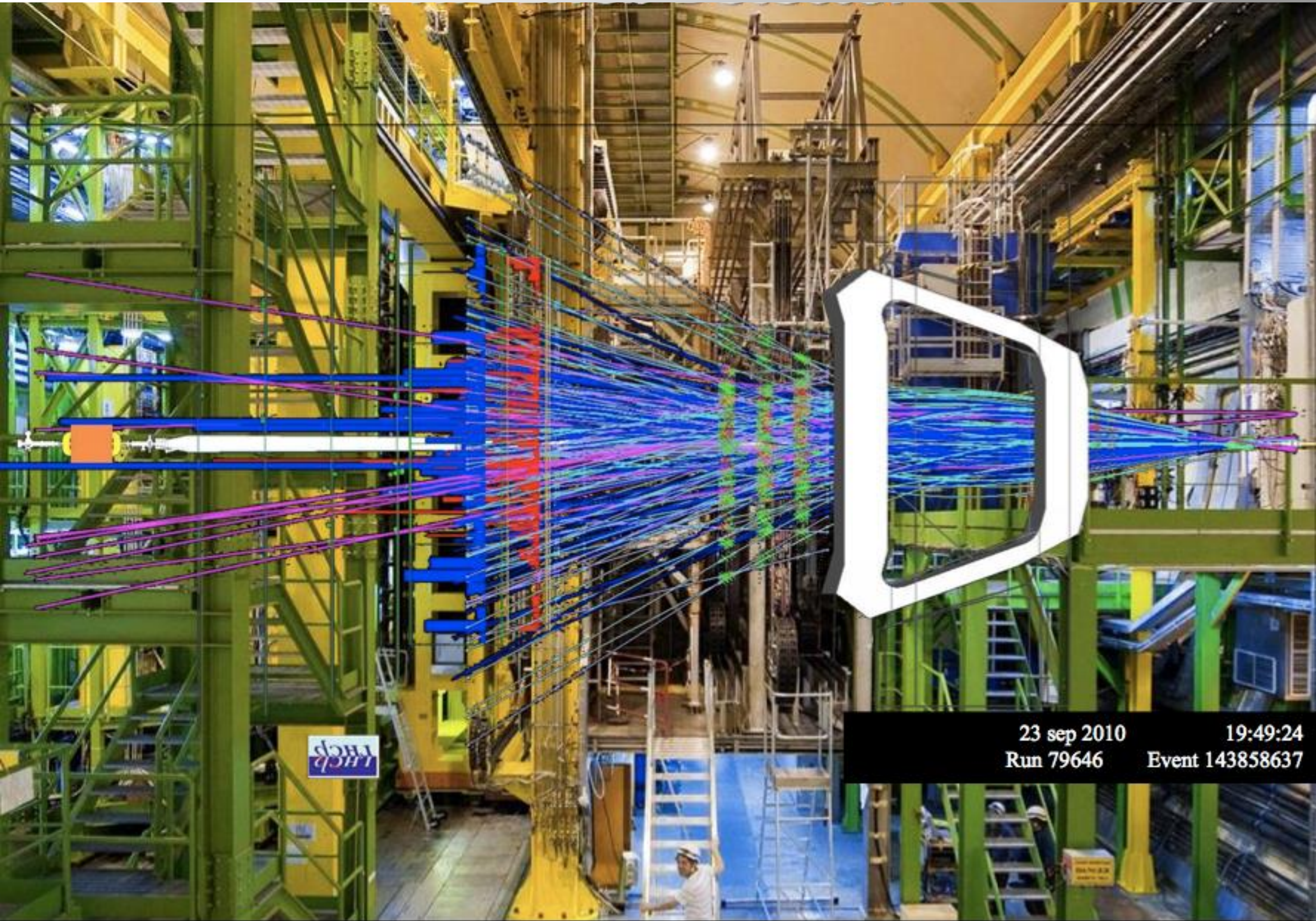
- Inject He, Ne, Ar into VELO at ~2×10^{-7} mbar
- Designed to measure beam profile
- Data taking in **fixed-target mode**

JINST 9 (2014) P12005

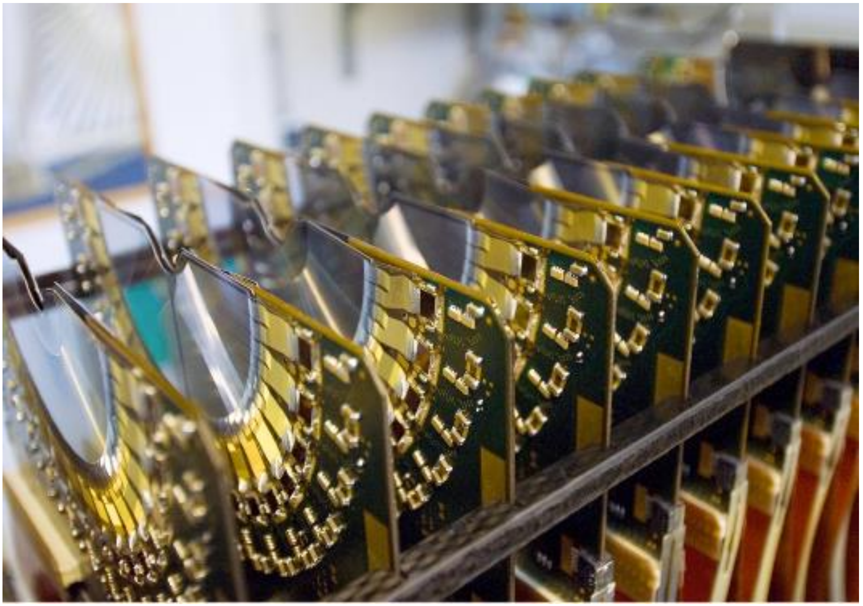
$\sqrt{s_{NN}}$ = 69, 110 GeV



LHCb operation

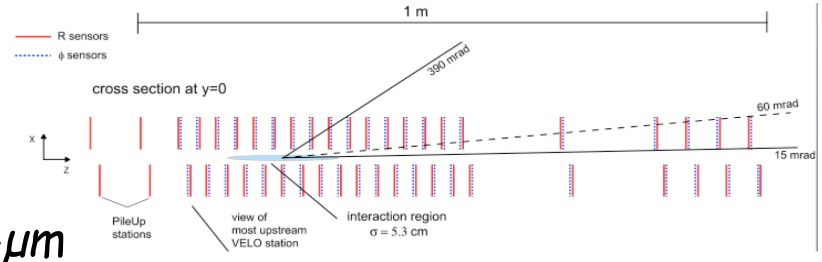


Vertex reconstruction in LHCb: VErtex LOcator



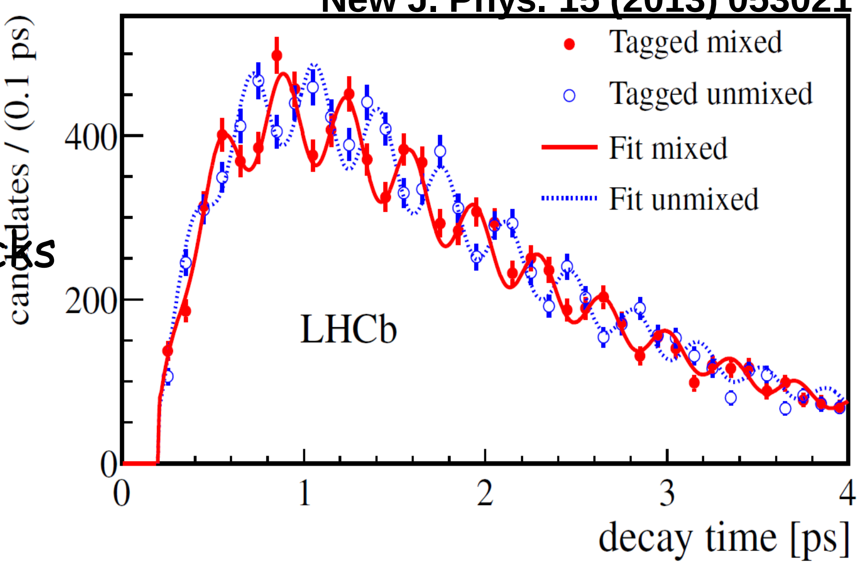
JINST 8 (2013) P08002, JINST 9 (2014) P09007

- 88 semi-circular **microstrip Si sensors**
- Double-sided, **R and φ** layout
- 300μm thick n-on-n sensors, strip pitches from 40 to 120μm
- **First active strip at 8mm from beam axis**



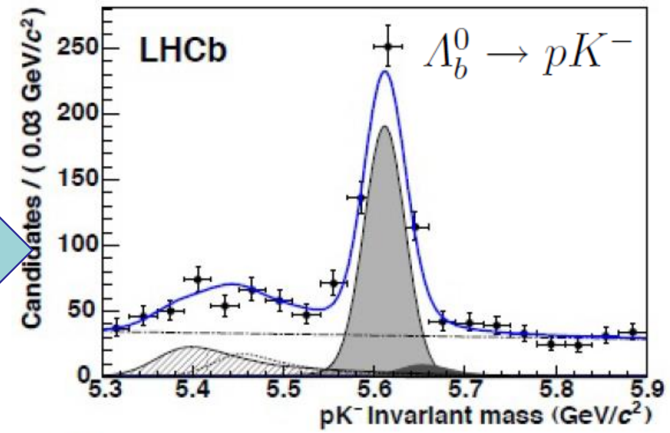
- Excellent **spatial resolution**, down to 4μm for single tracks
- Precise **impact parameter** measurement, $\sigma_{IP} = 11.6 + 23.4/pT \; [\mu m]$
- Precise **primary vertex** reconstruction, $\sigma_{x,y} = 13\mu m$, $\sigma_z = 69\mu m$ for vertex of 25 tracks
- Excellent **proper time** resolution
- **Vertex resolution** allows to resolve fast (x~27) $B_s\bar{B}_s$ oscillations

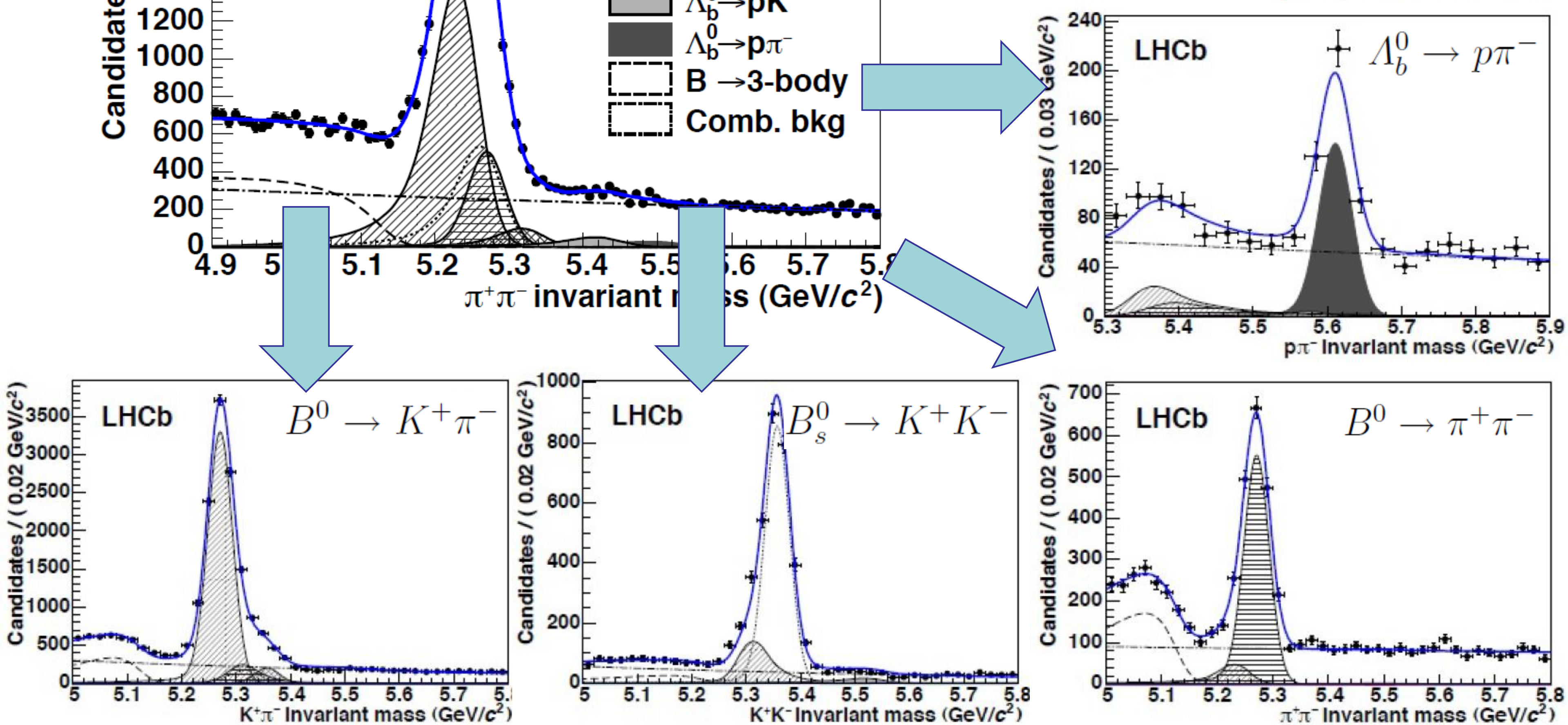
New J. Phys. 15 (2013) 053021



Charged hadron ID in LHCb: Cherenkov light detectors

- **2 Ring Imaging Cherenkov Detectors**
- Charged hadron ID, **charmless 2b b-hadron decays**





Charmonium production in pp collisions

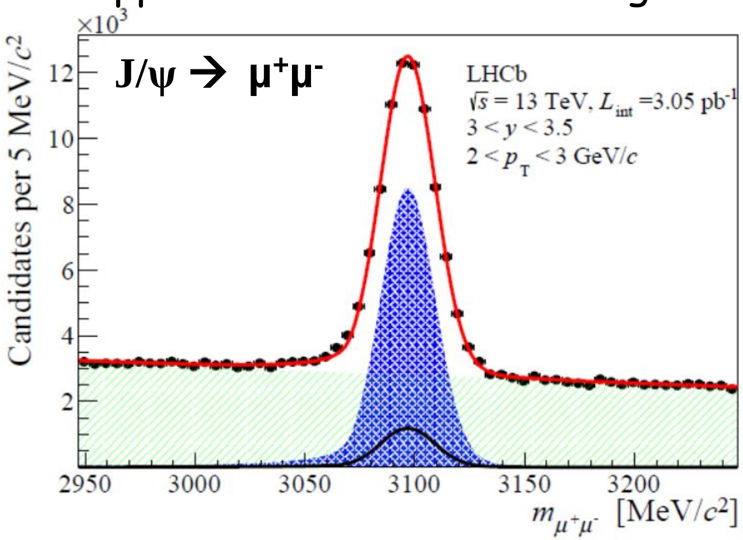
J/ψ production at √s = 13 TeV

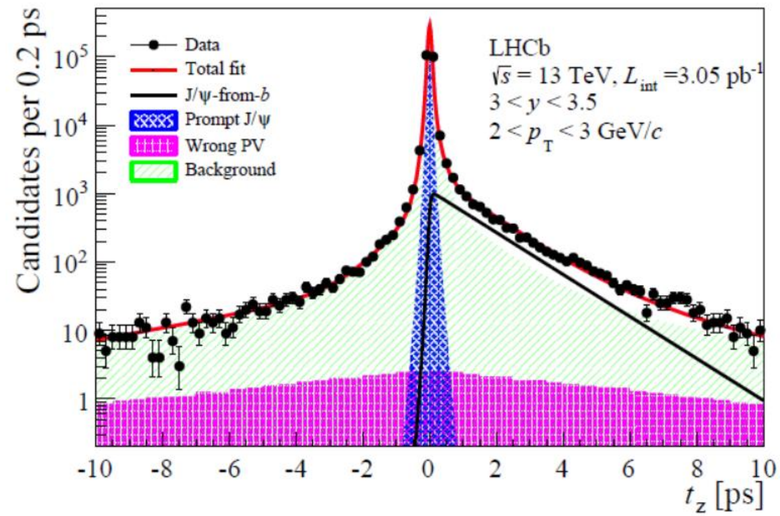
- **Prompt J/ψ production** and **production in b-hadron decays** extracted from the fit to pseudo-lifetime distribution

JHEP 1510 (2015) 172
JHEP 1705 (2017) 063
$\sqrt{s}$ = 13 TeV, $\int L dt \sim 3\ \mathrm{pb}^{-1}$

$$t_z = \frac{\left(z_{J/\psi} - z_{\mathrm{PV}}\right) \times M_{J/\psi}}{p_z}$$

Excellent **mass resolution** to suppress combinatorial background





Excellent **vertex resolution** to disentangle prompt production and production in b-decays

- Production **cross-section, integrated over acceptance** :

$$\boxed{\begin{aligned} \sigma(\text{prompt } J/\psi, p_{\mathrm{T}} < 14\,\mathrm{GeV}/c, 2.0 < y < 4.5) &= 15.03 \pm 0.03 \pm 0.94\,\mu\mathrm{b}, \\ \sigma(J/\psi\text{-from-}b, p_{\mathrm{T}} < 14\,\mathrm{GeV}/c, 2.0 < y < 4.5) &= 2.25 \pm 0.01 \pm 0.14\,\mu\mathrm{b}, \end{aligned}}$$

- **$b\bar{b}$ cross-section**, integrated over 4π : $\boxed{\sigma(pp \to b\bar{b}X) = 495 \pm 2 \pm 52\,\mu\mathrm{b},}$

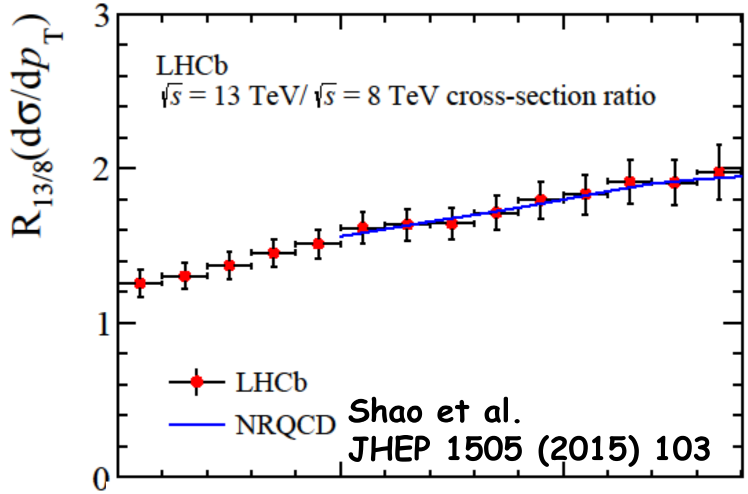
J/ψ production at √s = 13 TeV

- The **J/ψ production** measured **at √s = 13 TeV** and compared to that **at √s = 8 TeV** and **theory**

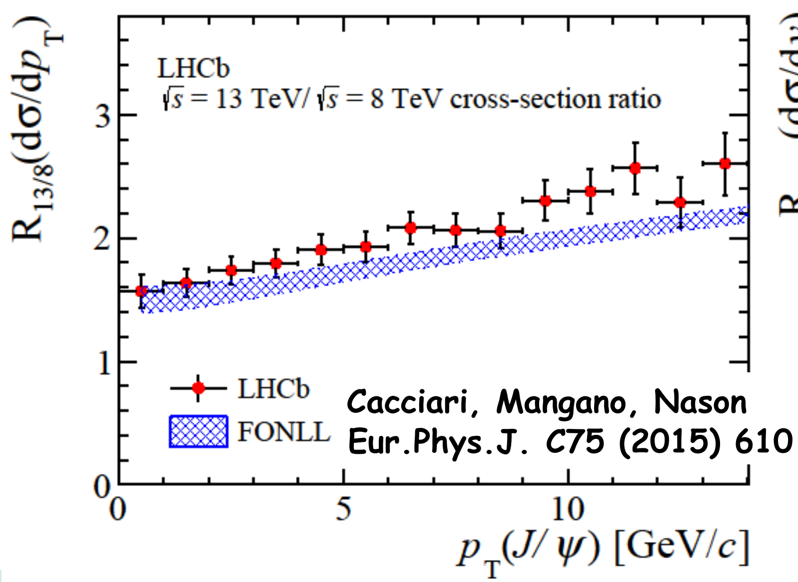
JHEP 1510 (2015) 172
JHEP 1705 (2017) 063

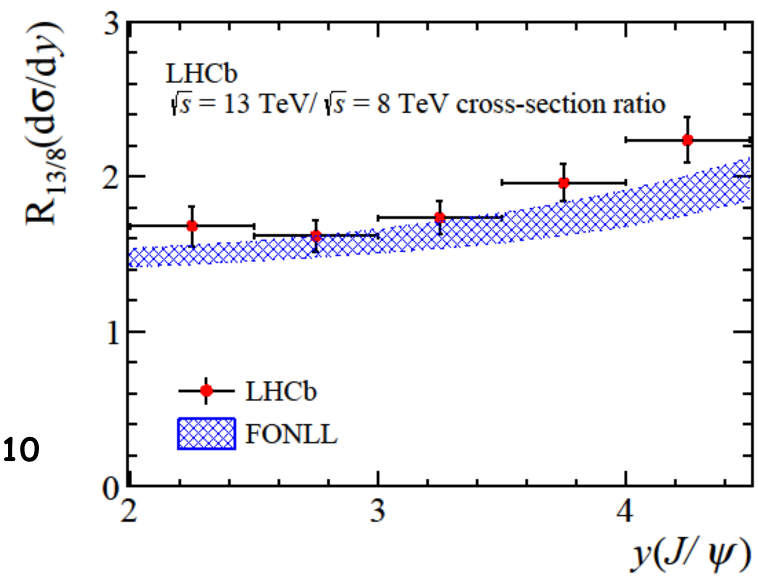
√s = 13 TeV, ∫Ldt ~ 3 pb^{-1}

- **Prompt production**



- **Production in b-decays**



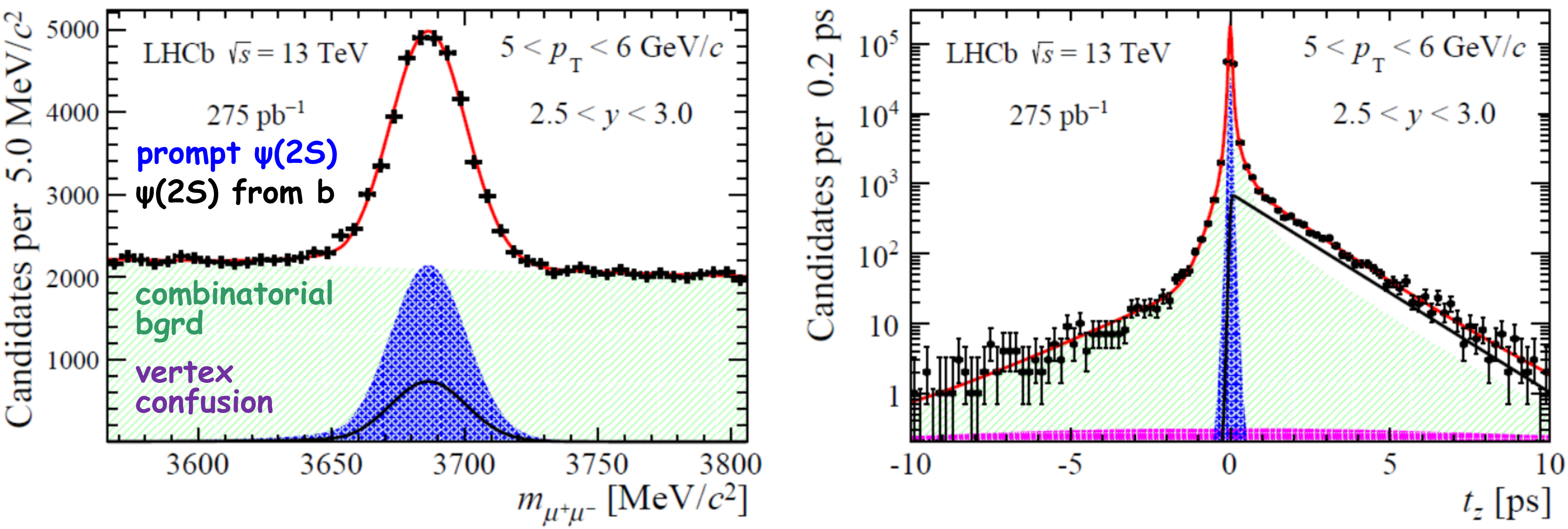


- Perfect (good) **theory-experiment agreement** for prompt (b-decay) production arXiv:1908.03099

$\sqrt{s}$ = 7, 13 TeV, $\int L dt$ ~ 614, 275 pb^{-1}

- **Negligible feed-down compared to J/ψ**
- **Prompt** (pp collision vertex) **ψ(2S) production** and **production in b-decays**
- Double differential cross-sections from two-dimensional fit in bins of p_T and y
- Prompt and b-decay components are extracted from the fit to pseudo-lifetime distribution

$$t_z = \frac{\left(z_{\psi(2S)} - z_{\rm PV}\right) \times M_{\psi(2S)}}{p_z}$$



- **Integral** cross sections:

$$\sigma(\text{prompt } \psi(2S), 7\,\text{TeV}) = 0.471 \pm 0.001\,(\text{stat}) \pm 0.025\,(\text{syst})\,\mu\text{b},$$
$$\sigma(\psi(2S)\text{-from-}b, 7\,\text{TeV}) = 0.126 \pm 0.001\,(\text{stat}) \pm 0.008\,(\text{syst})\,\mu\text{b}.$$

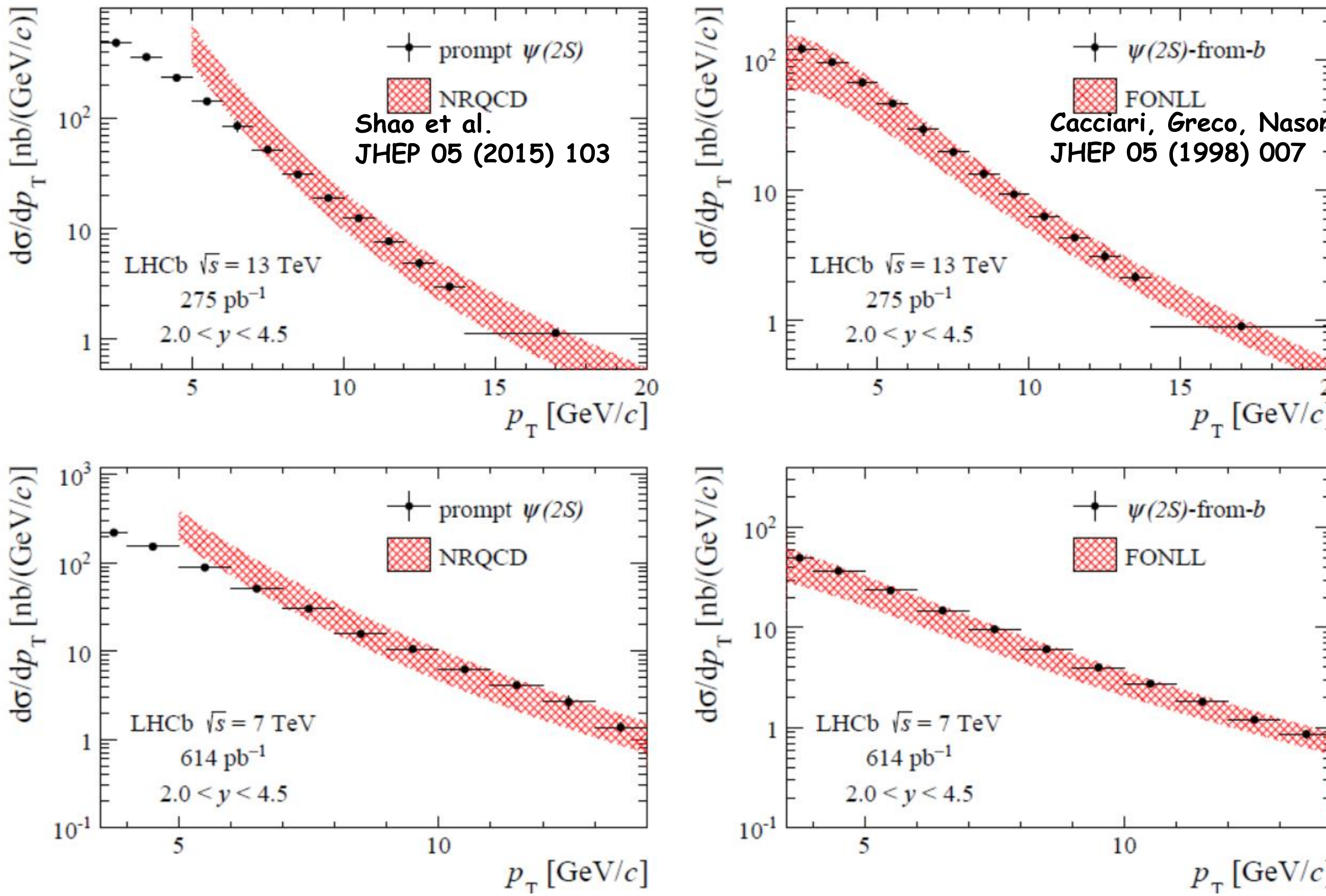
$$\sigma(\text{prompt } \psi(2S), 13\,\text{TeV}) = 1.430 \pm 0.005\,(\text{stat}) \pm 0.099\,(\text{syst})\,\mu\text{b},$$
$$\sigma(\psi(2S)\text{-from-}b, 13\,\text{TeV}) = 0.426 \pm 0.002\,(\text{stat}) \pm 0.030\,(\text{syst})\,\mu\text{b}.$$

ψ(2S) production at 7 and 13 TeV

- **Prompt ψ(2S) production** and **production in b-hadron decays**
- **Differential** cross sections

arXiv:1908.03099

$\sqrt{s}$ = 7, 13 TeV, $\int L dt \sim$ 614, 275 pb^{-1}



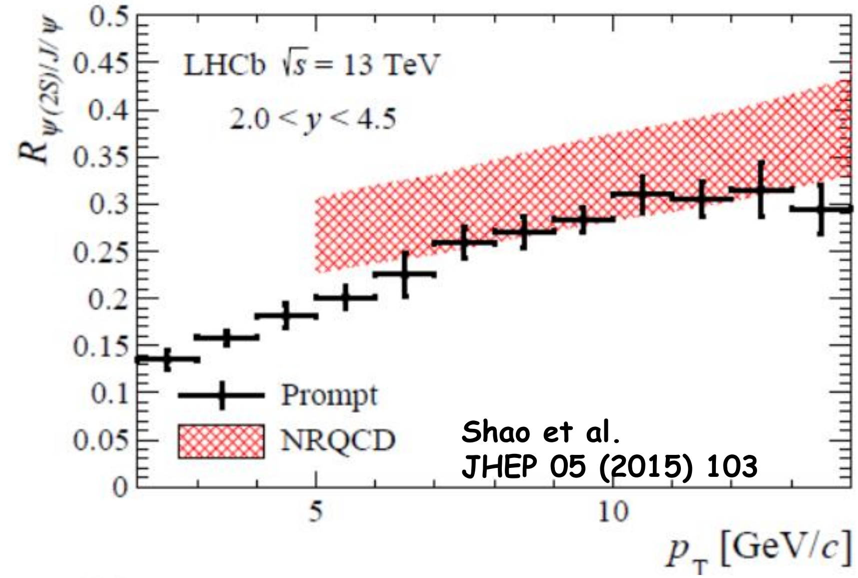
- Overall **good agreement with predictions, with deviation at low p_T** for prompt ψ(2S)
- New measurement at 7 TeV supersedes earlier result based on smaller event sample

ψ(2S) production at 7 and 13 TeV

arXiv:1908.03099

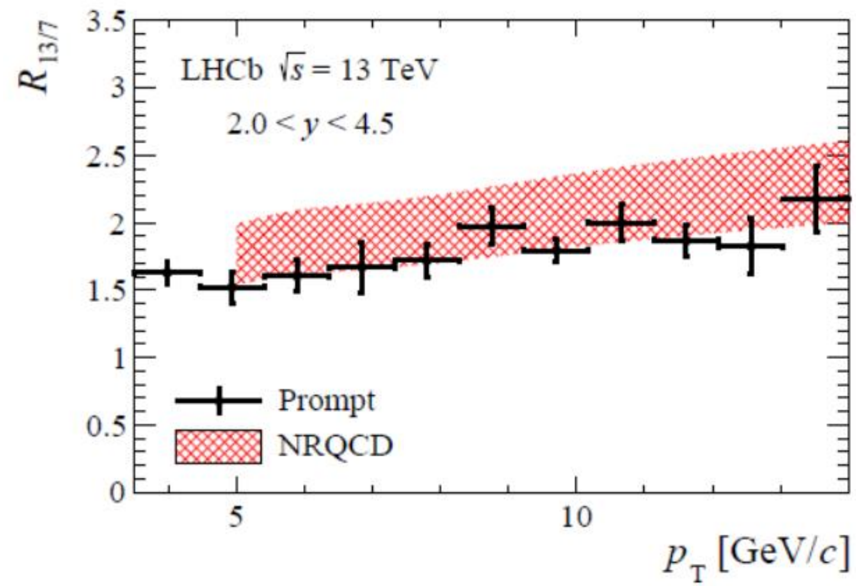
- Uncertainties partly cancel in ratios

$\sqrt{s}$ = 7, 13 TeV, $\int L dt$ ~ 614, 275 pb^{-1}



- Ratio between the ψ(2S) and J/ψ production cross-sections

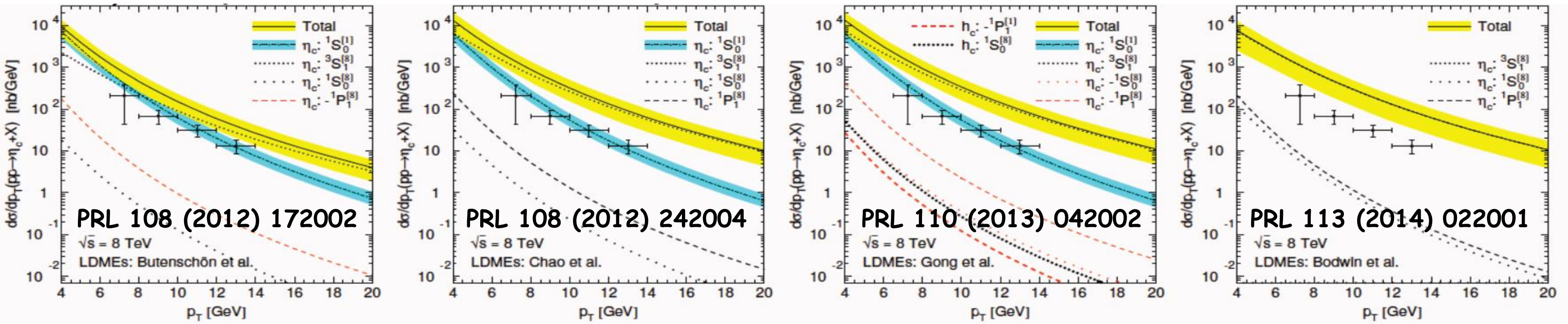
- Ratio between the ψ(2S) production cross-sections at $\sqrt{s}$ = 13 and 7 TeV



- **Overall good description** for both ratios
- Important to extend theory prediction to lower p_T

- Four LDMEs describing J/ψ production and polarization
- Linked to LDMEs describing $\eta_c(1S)$ production
- First $\eta_c(1S)$ prompt production measurement at 7, 8 TeV: LHCb **EPJC 75 (2015) 311** using $\eta_c(1S) \to p\bar{p}$

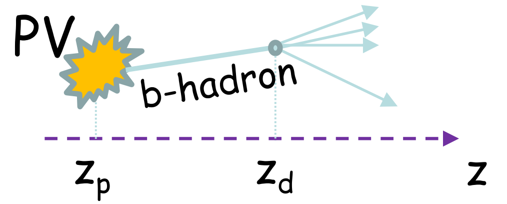
Butenschoen, He, Kniehl, **arXiv:1411.5287**



- Results described by **CS NLO**, below expected CO contribution
- New impressive progress in theory description, integrating LHCb result in LDME calculations:
  - Han, Ma, Meng, Shao, Chao **PRL 114 (2015) 092005**
  - Zhang, Sun, Sang, Li **PRL 114 (2015) 092006**
  - Baranov. Lipatov **EPJC 79 (2019) 621**
- Theory description still covers limited p_T range
- Further tests with **measurements at different √s and of other linked observables**

LHCb-PAPER-2019-024
$\sqrt{s}$ = 13 TeV, $\int L dt \sim 2\ fb^{-1}$

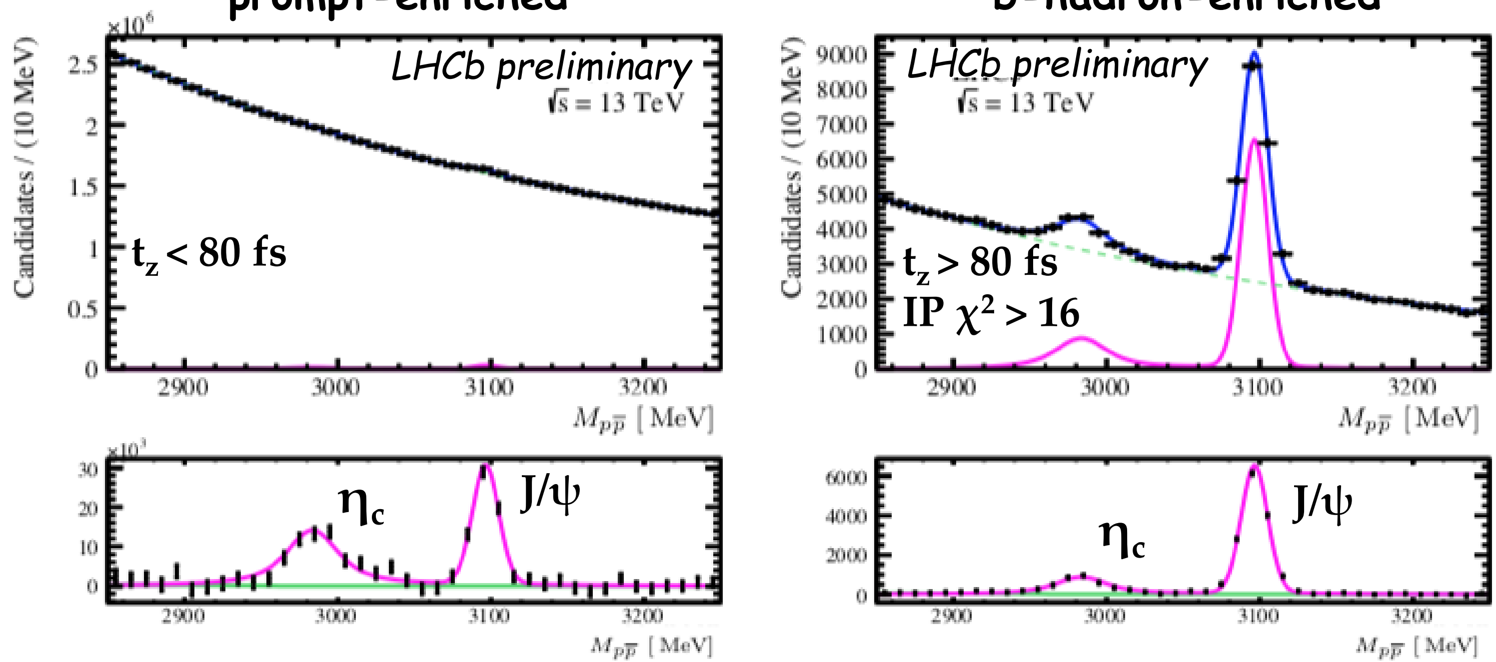
- **New analysis** with 13 TeV data, measurement relative to J/ψ
- **Selection** (as analysis at 7, 8 TeV) or pseudo proper-time fit (as J/ψ analyses)
- Pseudo proper-time to separate prompt charmonium and charmonium from b-decays



$$t_z = \frac{(z_d - z_p) M_{p\bar{p}}}{p_z}$$

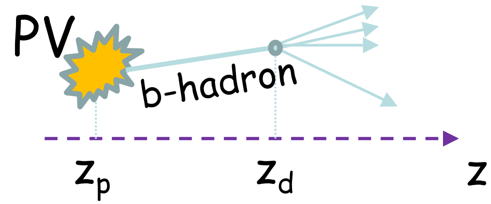
- Account for the cross feed

prompt-enriched **b-hadron-enriched**

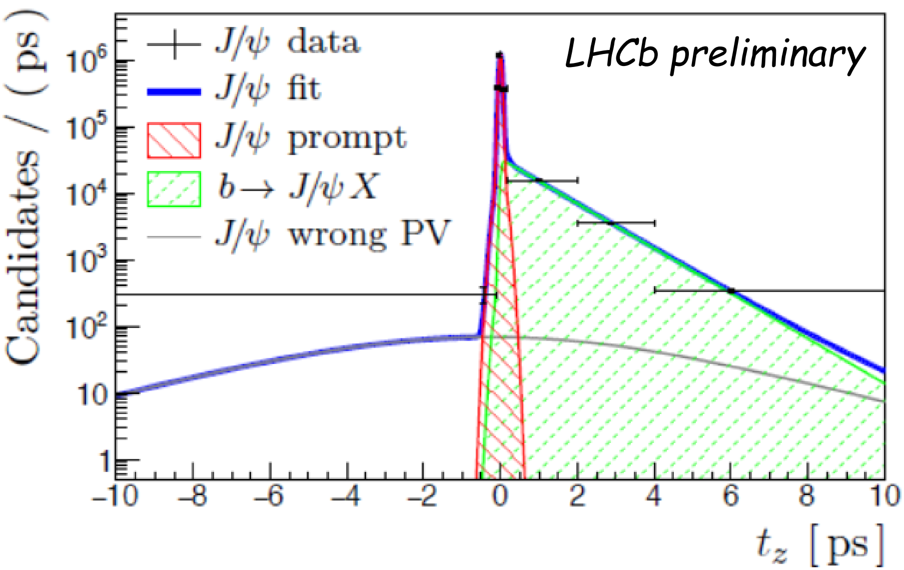


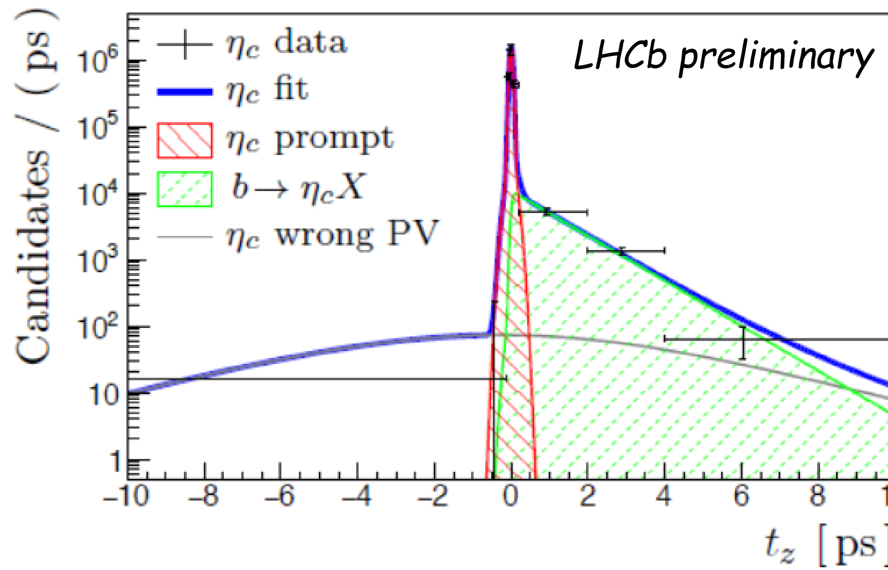
LHCb-PAPER-2019-024
$\sqrt{s}$ = 13 TeV, $\int L dt \sim 2\ fb^{-1}$

- **New analysis** with 13 TeV data, measurement relative to J/ψ
- Selection (as analysis at 7, 8 TeV) or **pseudo proper-time fit** (as J/ψ analyses)
- Pseudo proper-time to separate prompt charmonium and charmonium from b-decays



$$t_z = \frac{(z_d - z_p) M_{p\bar{p}}}{p_z}$$





LHCb-PAPER-2019-024
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- **New analysis** with 13 TeV data, measurement relative to J/ψ
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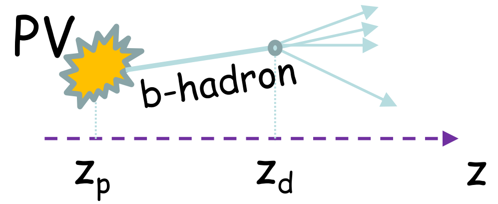
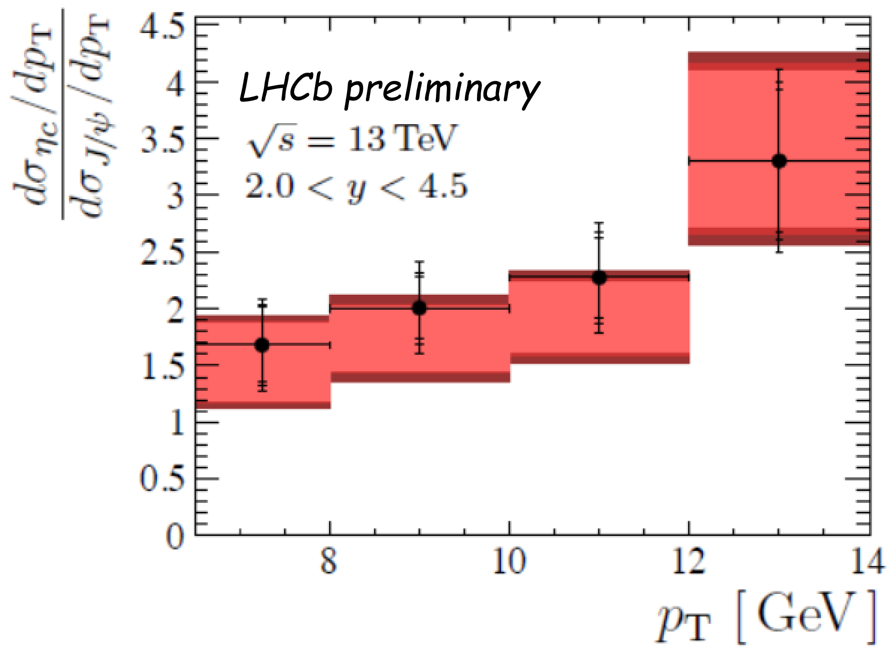
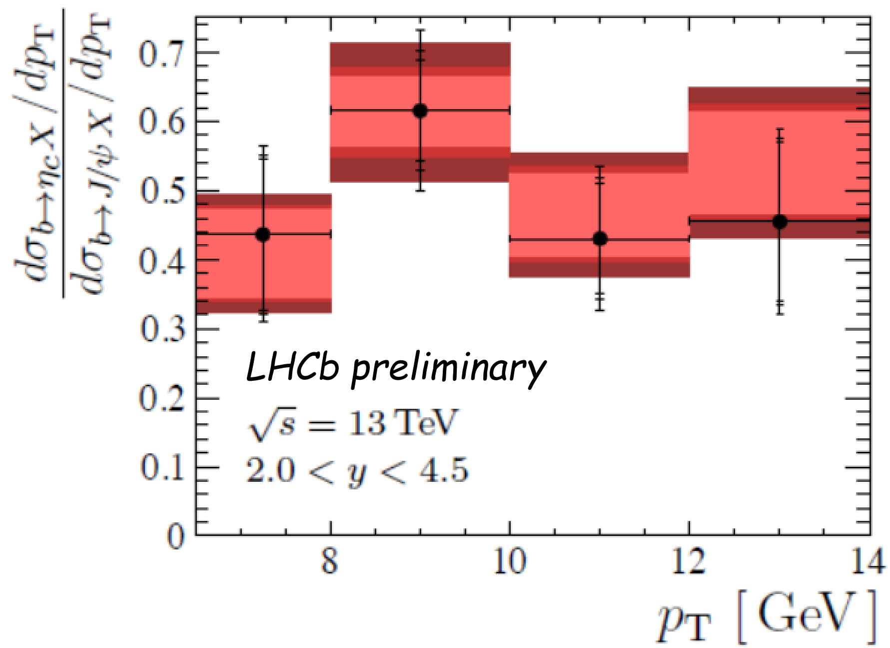


$$t_z = \frac{(z_d - z_p) M_{p\bar{p}}}{p_z}$$





- Both techniques yield **consistent results**

LHCb-PAPER-2019-024
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 2\ fb^{-1}$

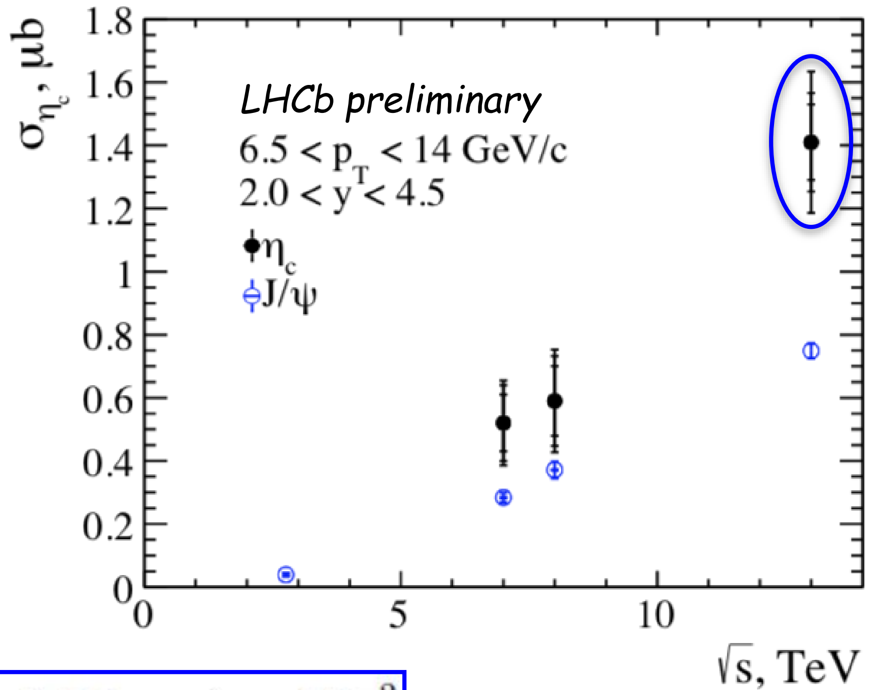
- **First measurement of $\eta_c(1S)$ production cross section at 13 TeV**

$$\left(\sigma_{\eta_c}\right)^{6.5\,\mathrm{GeV}<p_T<14.0\,\mathrm{GeV},\,2.0<y<4.5}_{13\,\mathrm{TeV}} = 1.26 \pm 0.11 \pm 0.08 \pm 0.14\ \mu\mathrm{b}$$

- Color Single model prediction: Feng,Shao,Lansberg,Zhang,Usachov,He **NPB 945 (2019) 114662**

$$1.56^{+0.83}_{-0.49}\ _{scale}\ {}^{+0.38}_{-0.17}\ _{CT14NLO}\ \mu\mathrm{b}$$

- **Consistent with being described by CSM**
- **Important to improve** (in particular, theory) **precision**
- $\sqrt{s}$ cross-section dependence



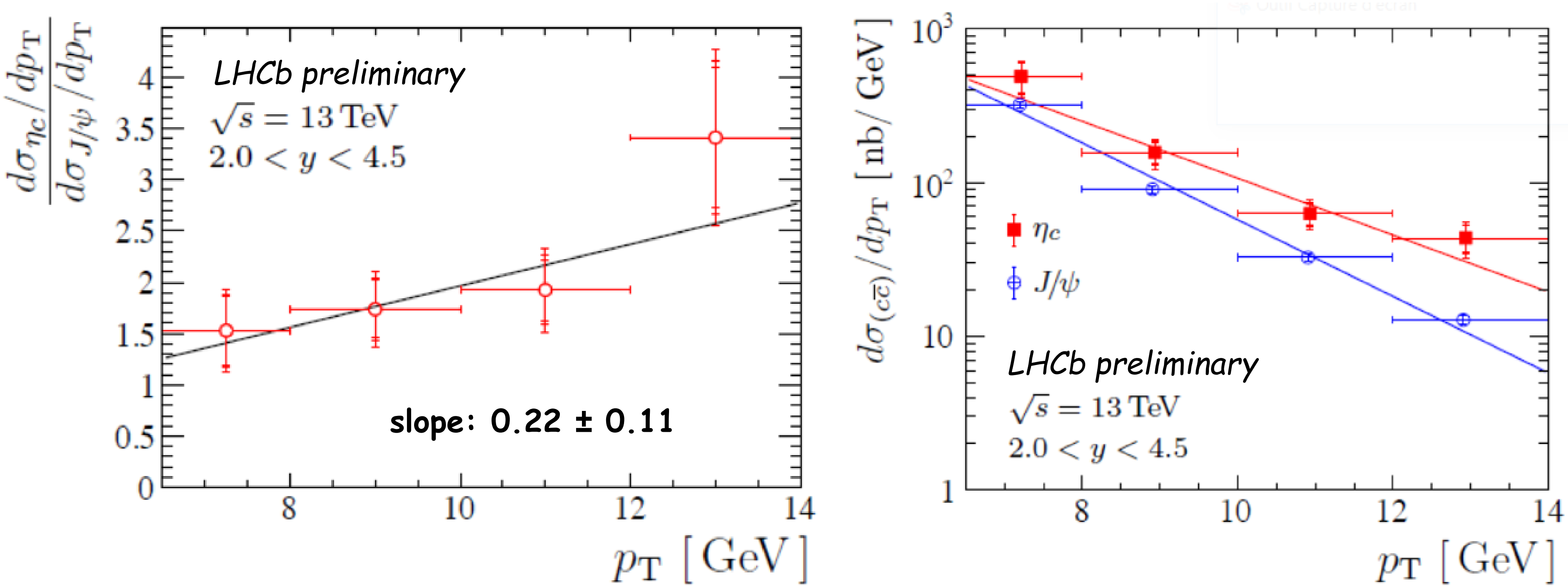
- **Inclusive production in b-decays:**

$$\mathcal{B}_{b\to\eta_c X} = (5.51 \pm 0.32_{stat} \pm 0.29_{syst} \pm 0.77_{norm}) \times 10^{-3}$$

- Consistent and more precise than the previous result

LHCb-PAPER-2019-024
$\sqrt{s}$ = 13 TeV, $\int L dt \sim 2\ fb^{-1}$

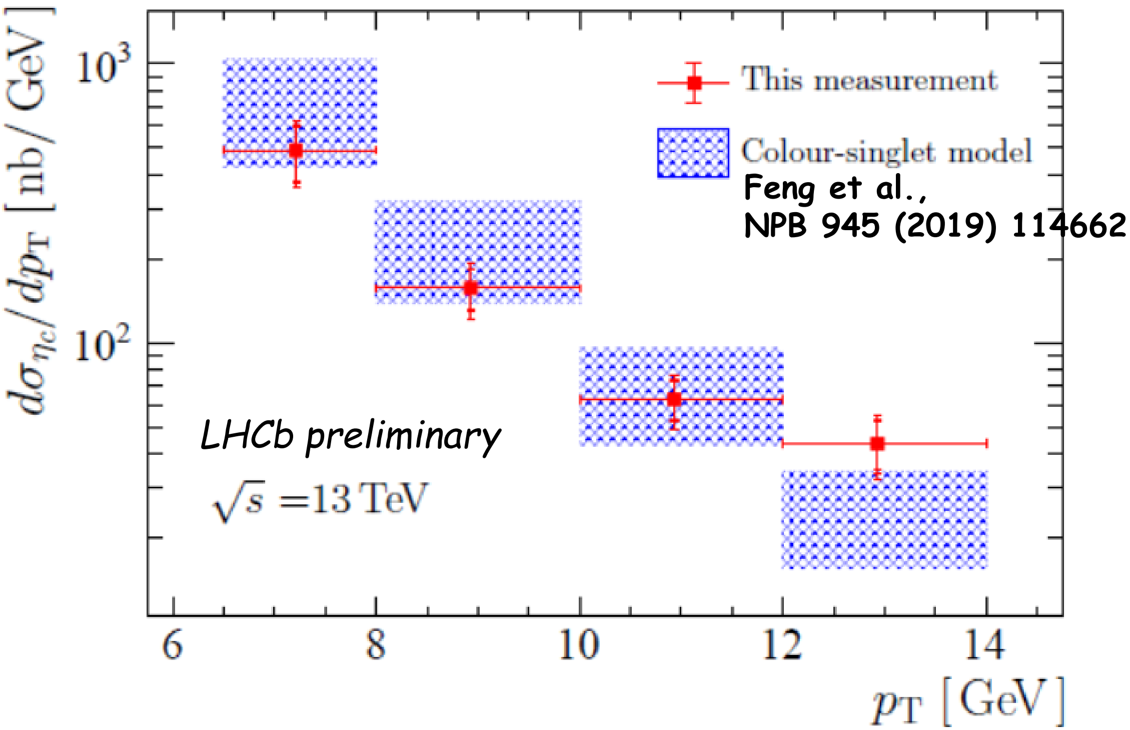
- **Integral cross-section consistent with being described by CSM**
- p_T-differential **prompt production**



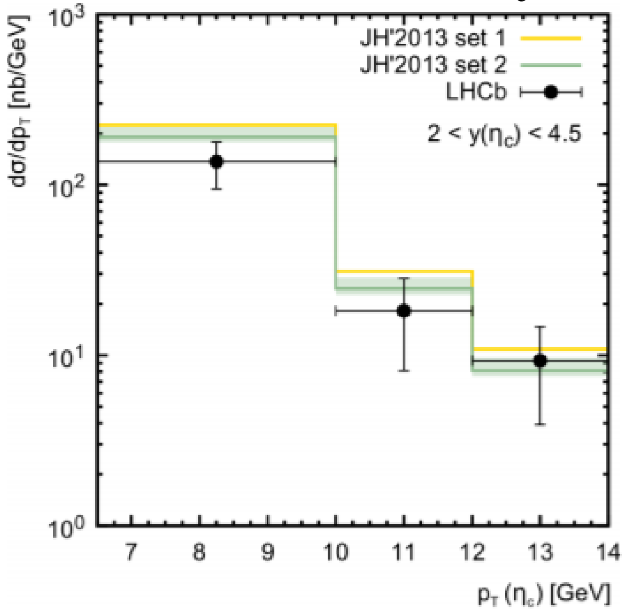
- An **indication of CO contribution at large** p_T ?

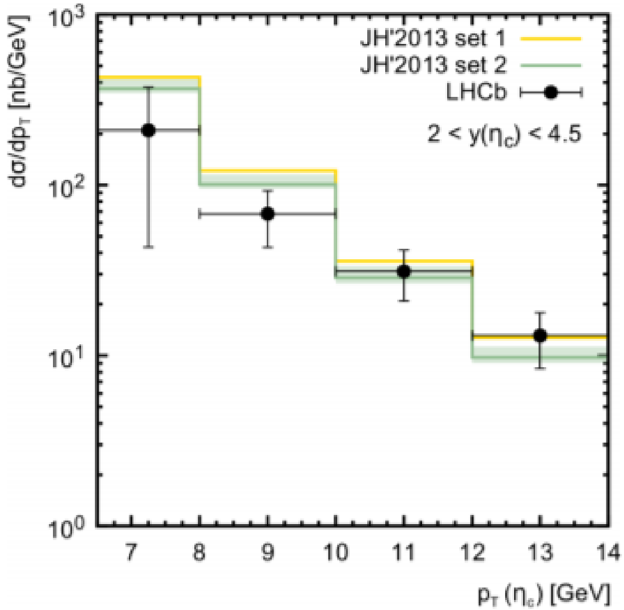
- **Integral cross-section consistent with being described by CSM**
- p_T-differential **prompt production**

Calculations in LHCb bins by Hua-Sheng Shao



LHCb-PAPER-2019-024
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 2\ fb^{-1}$





- Precision is critical
- Next step is to **constrain scale uncertainty**

EPJC 77 (2017) 609, PLB 769 (2017) 305

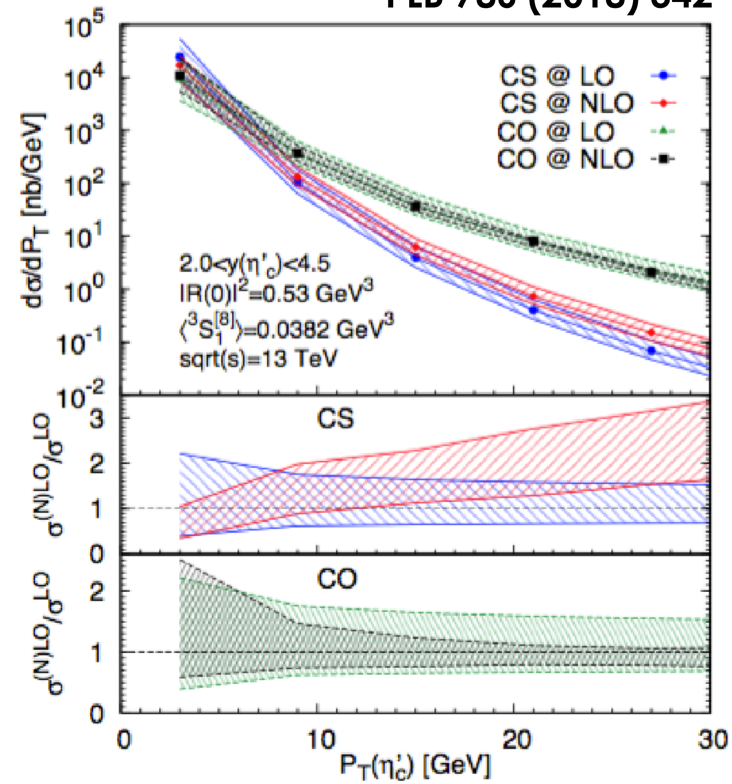
- LHCb measured **$\eta_c(2S)$ production in b-hadron decays**

$$\mathcal{B}(b \to \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi) = (6.34 \pm 1.81 \pm 0.57 \pm 1.89_{\mathrm{BR}}) \times 10^{-7}$$

$$\mathcal{B}(B^+ \to \eta_c(2S)K^+) \times \mathcal{B}(\eta_c(2S) \to p\bar{p}) = (3.47 \pm 0.72 \pm 0.20 \pm 0.16_{\mathrm{BR}}) \times 10^{-8}$$

- Similar to J/ψ and $\eta_c(1S)$, but **feed-down free system: $\psi(2S)$ and $\eta_c(2S)$**
- Motivated by theory calculations
- **Dedicated LHCb trigger in 2018**

Lansberg, Shao, Zhang
PLB 786 (2018) 342



- To be described **simultaneously with $\psi(2S)$ production**

Playing phenomenology with charmonium states

- From **EPJC 75 (2015) 311** and **Chin. Phys. C40 (2016)**

$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)} = 0.691 \pm 0.090 \pm 0.024 \pm 0.103_{BR}$$

- Relation between LDME from HQSS:

$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle O_8^{J/\psi}(^3P_0)\rangle.$$

- Branching fractions calculated in **Beneke, Maltoni, Rothstein** **PRD 59 (1999) 054003**

Usachov, Shao et al.

Shao et al., PRL 114 (2015) 092005
Baranov. Lipatov, EPJC 79 (2019) 621
Butenschoen, Kniehl, PRD 84 (2011) 051501

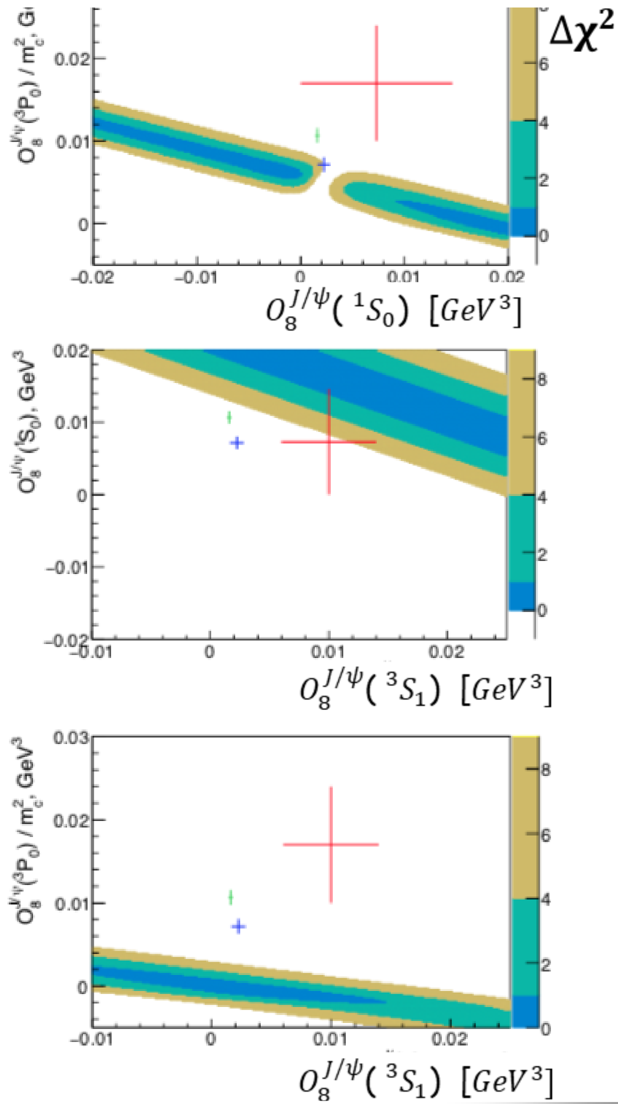
- Fix CS LDME from potential model

$$\langle O_8^{J/\psi}(^3S_1)\rangle = 1.16\,\mathrm{GeV}^3$$

- **Fit three LDME to two measurements**

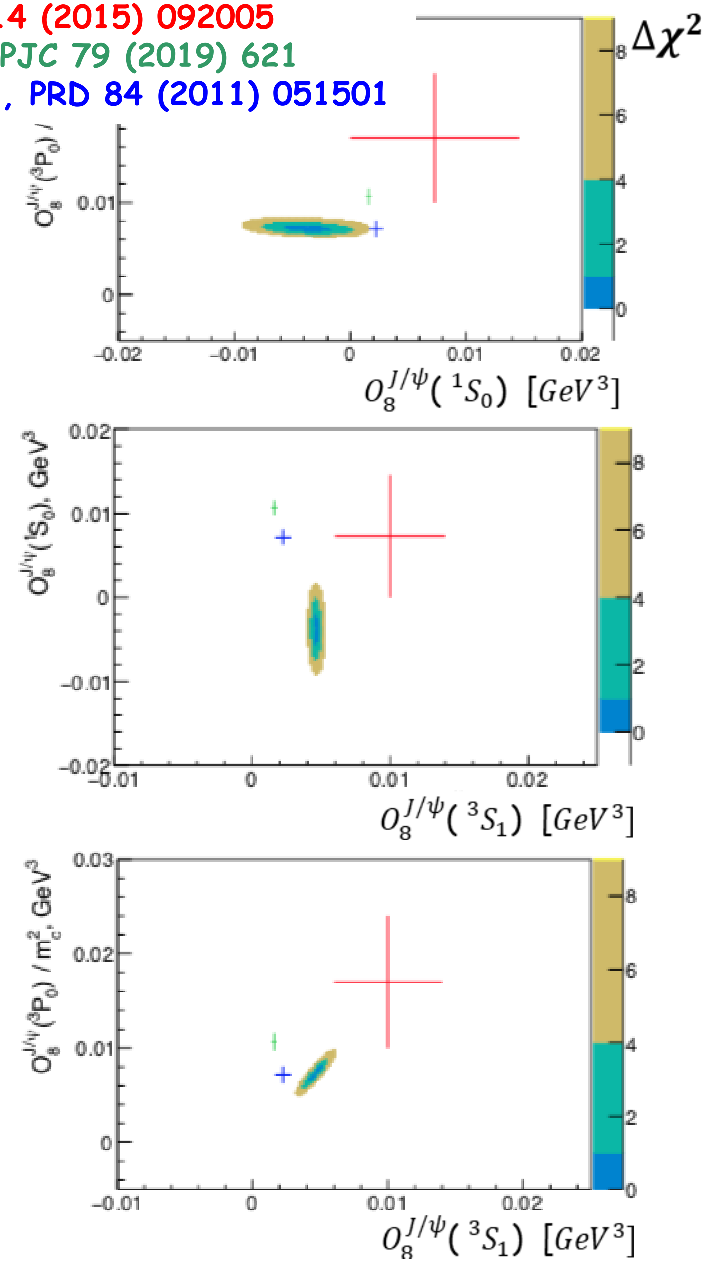
$$\boxed{\frac{\mathcal{B}(b \to \eta_c(1S)^{direct}X)}{\mathcal{B}(b \to J/\psi^{direct}X)}} \quad \boxed{\mathcal{B}(b \to J/\psi^{direct}X)}$$

- Consecutively fix remaining LDME from **Chao et al.,** PRL 108 (2012) 242004
- **Theory calculations should be revisited**, higher order corrections maybe needed



Shao et al., PRL 114 (2015) 092005
Baranov. Lipatov, EPJC 79 (2019) 621
Butenschoen, Kniehl, PRD 84 (2011) 051501

- Simultaneous fits to J/ψ and $\eta_c(1S)$ LDMEs, prompt and b-decay production
- **Short distance coefficients** for prompt production from H.-S. Shao



Usachov, Kou, SB, LAL-17-051

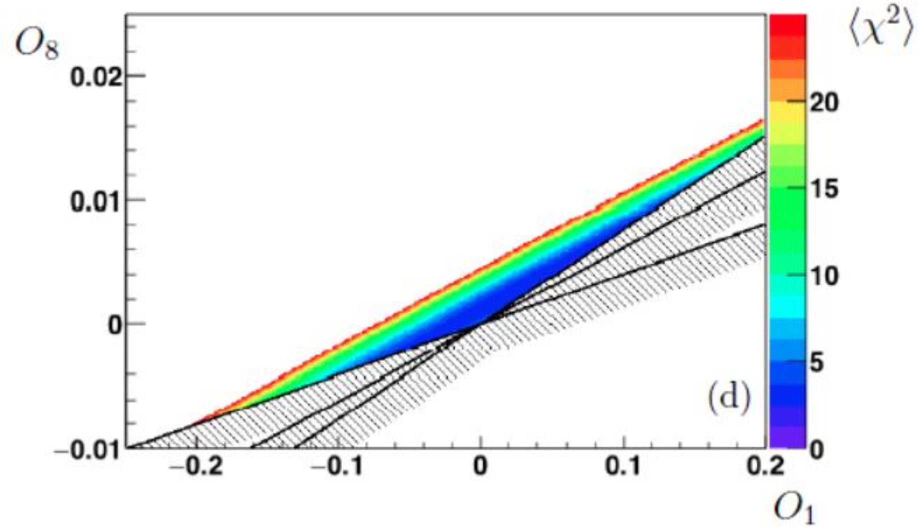
- From **EPJC 77 (2017) 609** and **Chin. Phys. C40 (2016) 100001**:

$$\mathcal{B}(b \to \chi_{c0}{}^{direct} X) = (2.74 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c1}{}^{direct} X) = (2.49 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c2}{}^{direct} X) = (0.89 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}}) \times 10^{-3}$$

- Relation between LDME from HQSS:

$$O_1 \equiv \langle O_1^{\chi_{c0}}({}^3P_0)\rangle / m_c^2,$$
$$O_8 \equiv \langle O_8^{\chi_{c0}}({}^3S_1)\rangle,$$
$$\langle O_1^{\chi_{cJ}}({}^3P_J)\rangle / m_c^2 = (2J+1) O_1,$$
$$\langle O_8^{\chi_{cJ}}({}^3S_1)\rangle = (2J+1) O_8.$$

- Branching fractions calculated in
  Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003



- **Fit two LDME to three measurements**

- Important to **revisit theory calculations**

- This technique constrains theory using **simultaneously** results on **charmonia hadroproduction and** on **charmonia from b-inclusive decays** under **assumptions of factorization, universality and HQSS**, with **different charmonium states**

- Alternatively, once hadroproduction and production in b-decays measured for charmonium states with linked LDMEs,
  the above **assumptions can be tested quantitatively**

Intermezzo: selected results on production of Y(nS) states

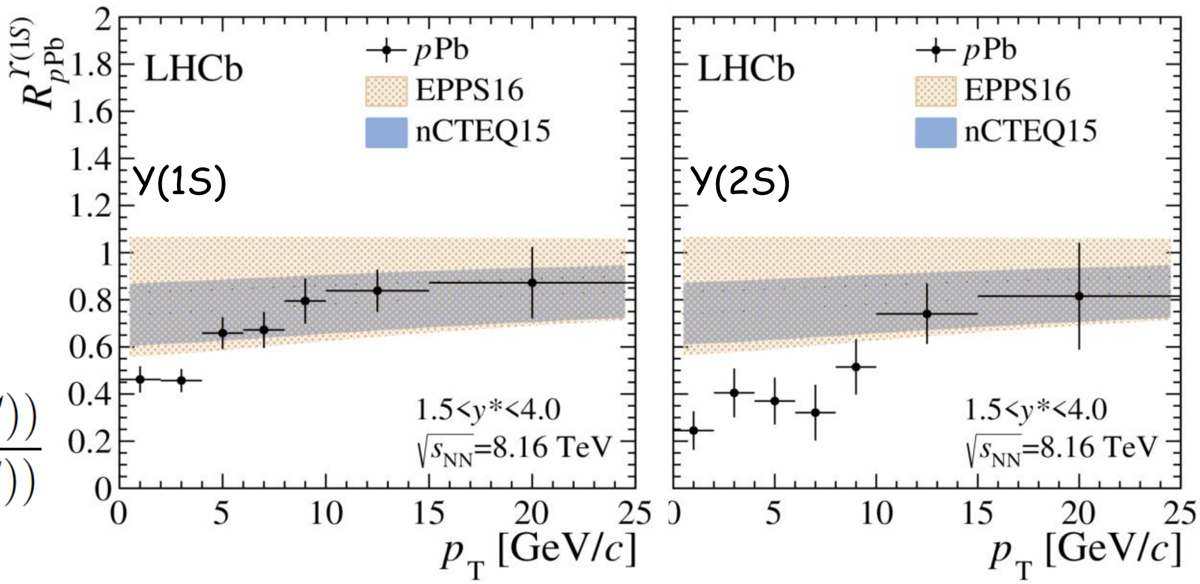
JHEP 11 (2018) 194

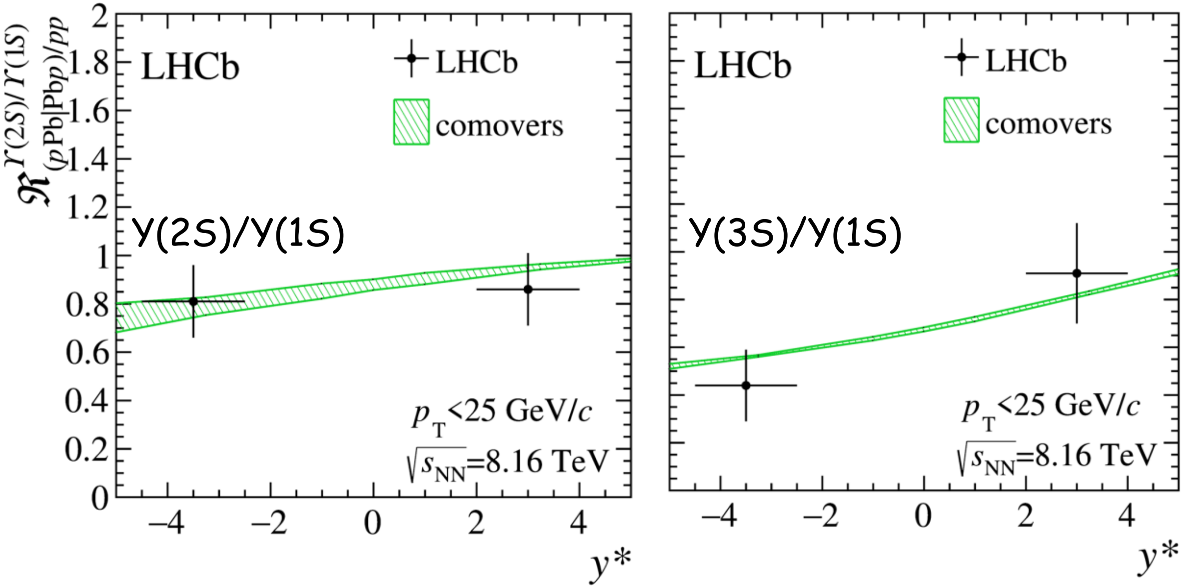
$\sqrt{s_{NN}}$ = 8.16 TeV, $\int L dt$ ~ 7.6 nb^{-1}

- **Double differential cross-sections** $d^2\sigma/dp_T dy$ **for Υ(1S) and Υ(2S), integral for Υ(3S)**
- **Nuclear modification R enhanced at low p_T**
- Agreement with HELAC-Onia predictions at high p_T

- Suppression factor

$$R(\Upsilon(nS)) = \frac{[\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}dy^*]\,(\Upsilon(nS))}{[\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}dy^*]\,(\Upsilon(1S))}$$





JHEP 11 (2018) 194

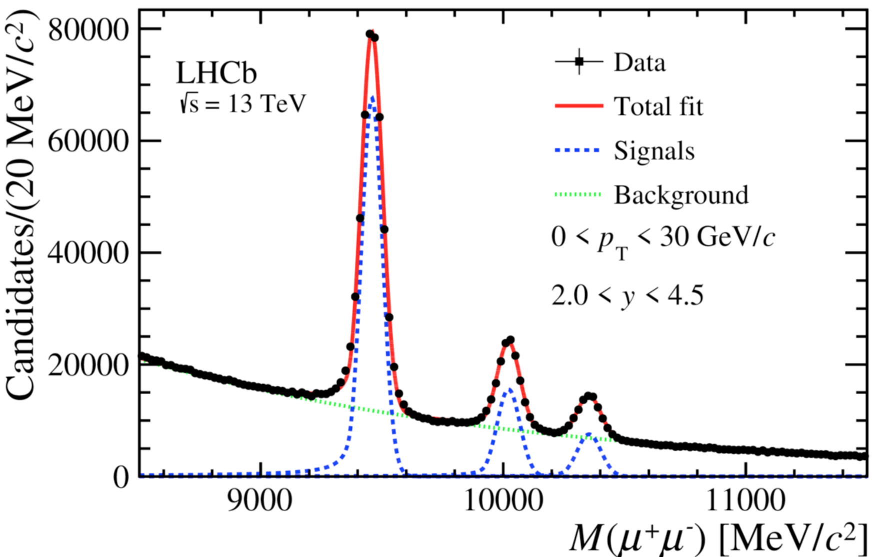
$\sqrt{s_{NN}}$ = 8.16 TeV, $\int Ldt$ ~ 7.6 nb^{-1}

- **Suppression of n > 1 states** in agreement with predictions and previous measurements
- Stronger suppression at low p_T
- **Nuclear modification of suppression factor** $\mathfrak{R}^{\Upsilon(nS)/\Upsilon(1S)}_{(p\mathrm{Pb}|\mathrm{Pb}p)/pp} = \frac{R(\Upsilon(nS))_{p\mathrm{Pb}|\mathrm{Pb}p}}{R(\Upsilon(nS))_{pp}}$
- Enhanced suppression of Υ(3S) in pPb compared to pp at negative rapidity
- **All three Υ(nS) states suppressed** with sequential suppression ordering R_{AA} (Υ(1S)) > R_{AA} (Υ(2S)) > R_{AA} (Υ(3S))

Υ(nS) production at 13 TeV

JHEP 07 (2018) 134
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 277\ pb^{-1}$

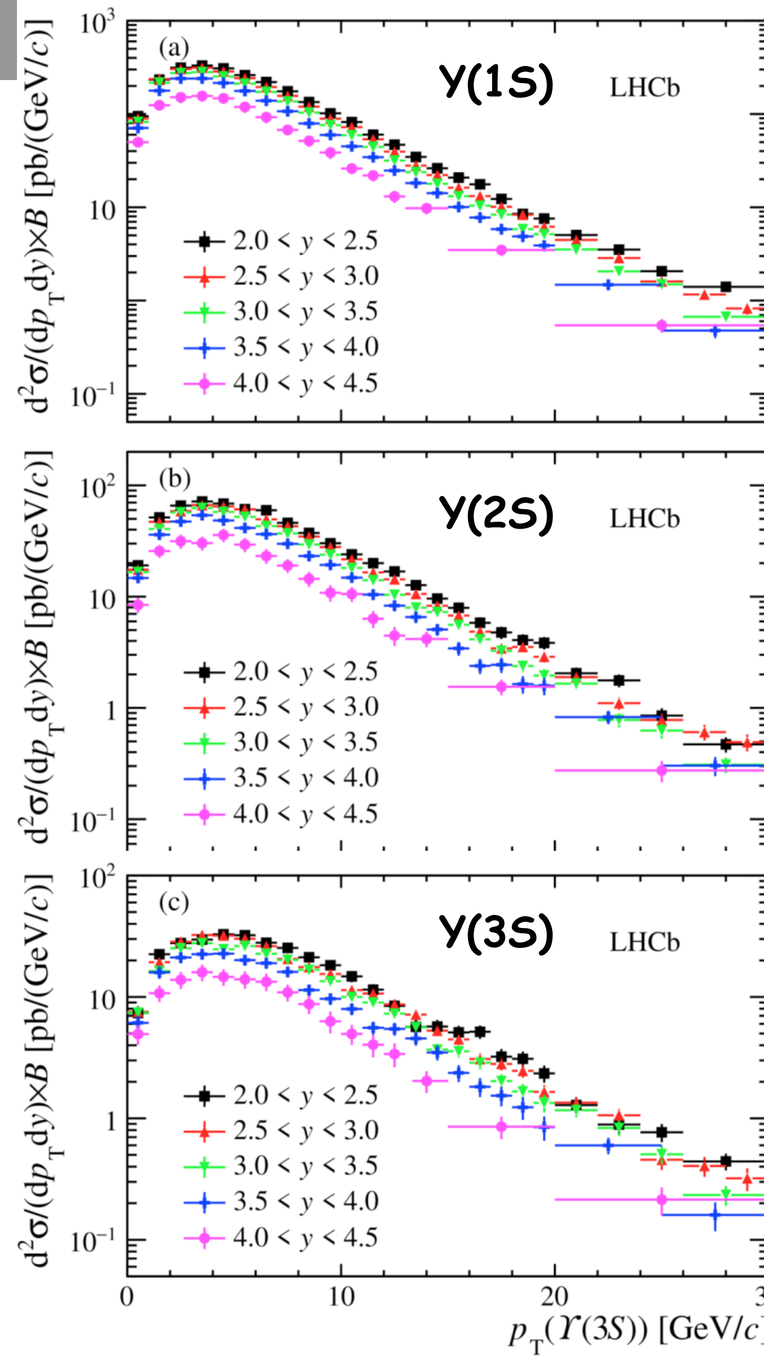
- Clean signals from Υ(nS)→μμ decays



- Assume no polarization
- **Integral cross-sections of Υ(1S), Υ(2S) and Υ(3S)** in the LHCb fiducial region $0 < p_T < 15$ GeV/c, $2.0 < y\ 4.5$:

$$4687 \pm 10 \pm 294\ \text{pb}$$
$$1134 \pm 6 \pm 71\ \text{pb}$$
$$561 \pm 4 \pm 36\ \text{pb}$$

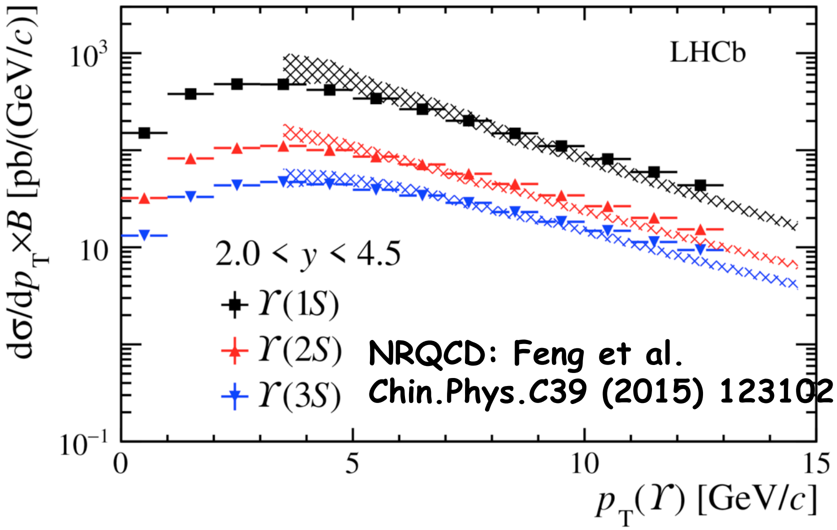
- **Double differential cross-sections** $d^2\sigma/dp_T dy \times BR(\Upsilon(nS)\to\mu\mu)$



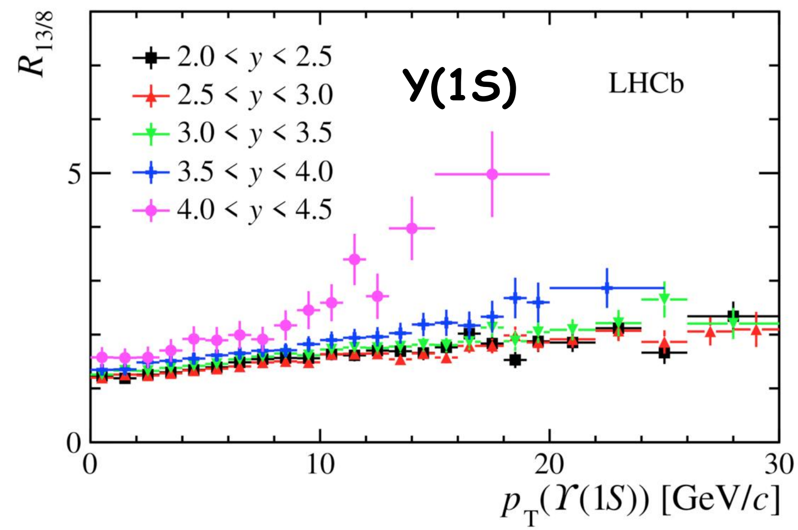
JHEP 07 (2018) 134

$\sqrt{s}$ = 13 TeV, $\int L dt \sim 277\ pb^{-1}$

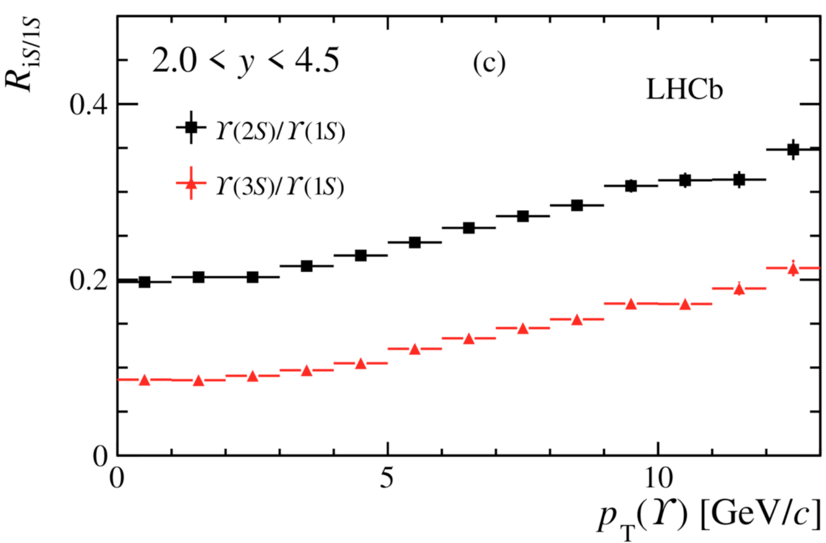
- **p_T-differential cross-sections**
  $d^2\sigma/dp_T dy \times BR(\Upsilon(nS)\rightarrow\mu\mu)$



- **Ratio of cross sections: 13 and 8 TeV**



- **Good agreement with NRQCD** predictions
- Cross-section **ratios between Υ(nS) states**



- Consistently above unity
- Growths with p_T and y for all states

- **Suppression of n>1 states at low p_T**
- No significant dependence on y
- Increasing suppression of higher states: **indication of melting in pp collisions ?**

- **Other phenomena** typically thought only to occur in collisions of large nuclei have been **observed in high multiplicity pp collisions**: a near-side ridge in two-particle angular correlations, strangeness enhancement, and collective flow

CMS collab., JHEP 09 (2010) 091
ALICE collab., Nature Phys. 13 (2017) 535
CMS collab., PLB 765 (2017) 193

- **High-multiplicity pp collisions** plausibly **emulate a hadronic environment that approaches heavy ion collisions** in many respects

Probing charmonium-like states

Multiplicity dependent production of $\chi_{c1}(3872)$ and $\psi(2S)$

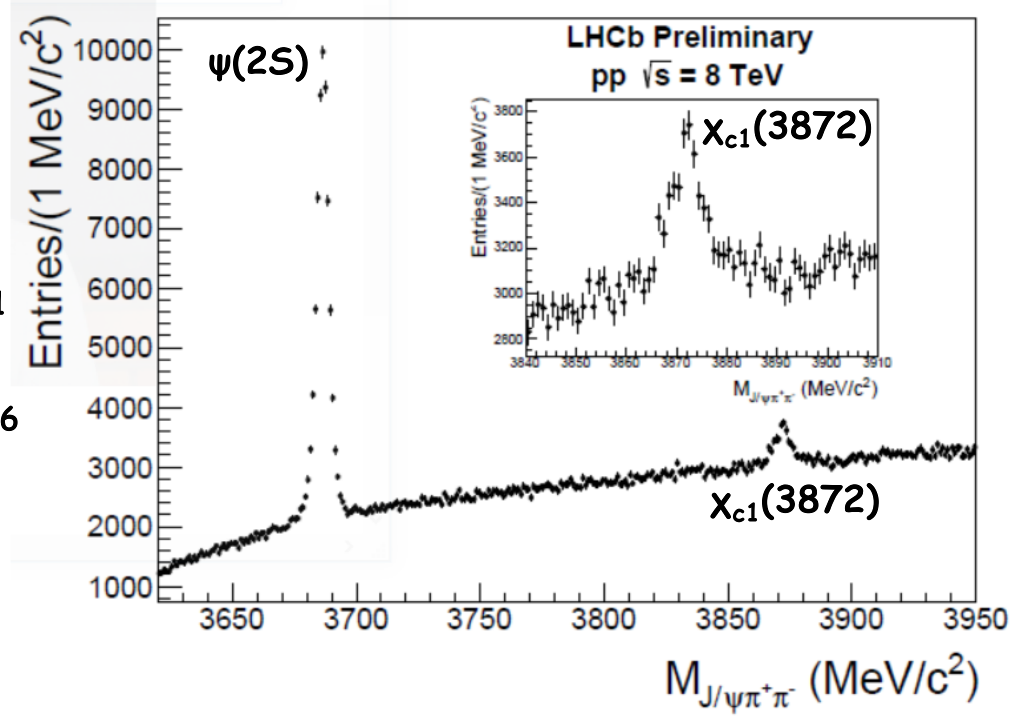
- One of the explanations of χ_{c1}**(3872)** is a hadronic molecule, a state consisting of D and $\bar{D}$ bound via pion exchange

LHCb-CONF-2019-005

$\sqrt{s}$ = 8 TeV, $\int Ldt$ ~2 fb^{-1}

- Then small binding energy, 0.01 ± 0.27 MeV, and large radius ~7 fm

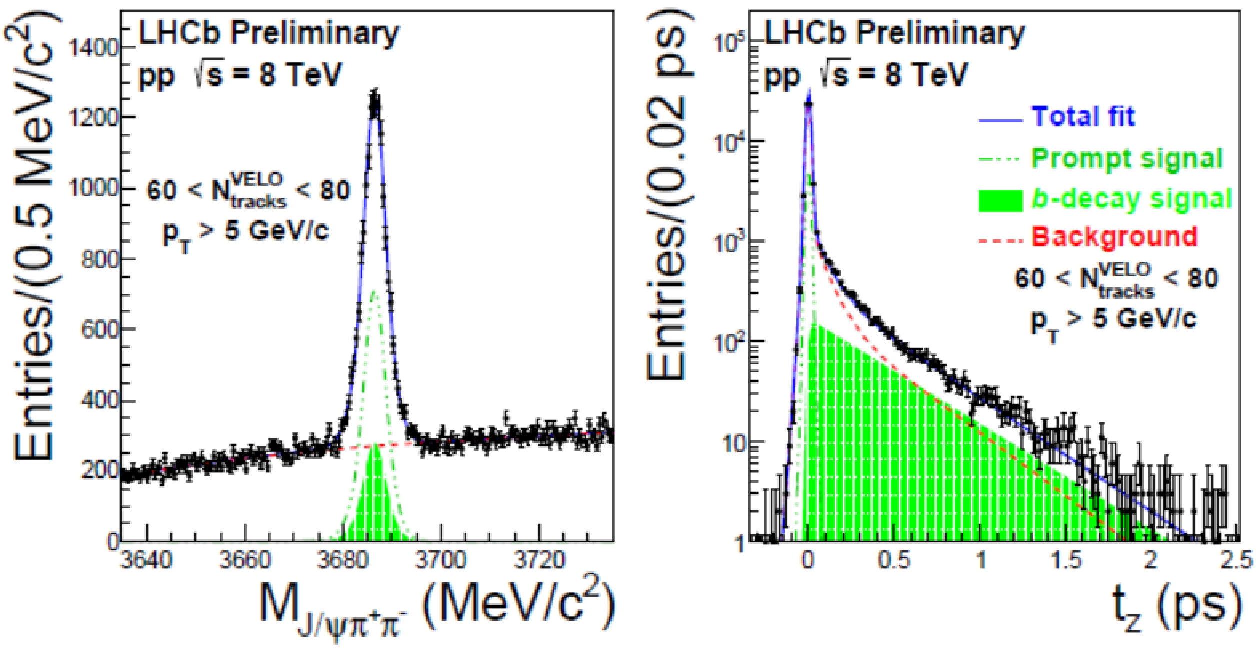
S.Coito, G.Rupp, E.van Beveren, EPJC 73 (2013) 2351
N.A.Tornqvist, PLB 590 (2004) 209
E.Braaten, M.Kusunoki, PRD 71 (2005) 074005
M.Cardoso, G.Rupp, E.van Beveren, EPJC 75 (2015) 26



- Distinguish prompt and b-decay components using pseudo proper-time
- Measure **ratios, $\chi_{c1}(3872)$ and $\psi(2S)$, for prompt and b-decay components**

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]} = \frac{N_{\chi_{c1}(3872)}\, f_{\rm prompt}^{\chi_{c1}(3872)}}{N_{\psi(2S)}\, f_{\rm prompt}^{\psi(2S)}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{\chi_{c1}(3872)}}$$

- **Simultaneous fit to mass and pseudo proper-time in bins of event activity**
- Example of **fit projections for ψ(2S)** in the event activity bin 60 < N < 80



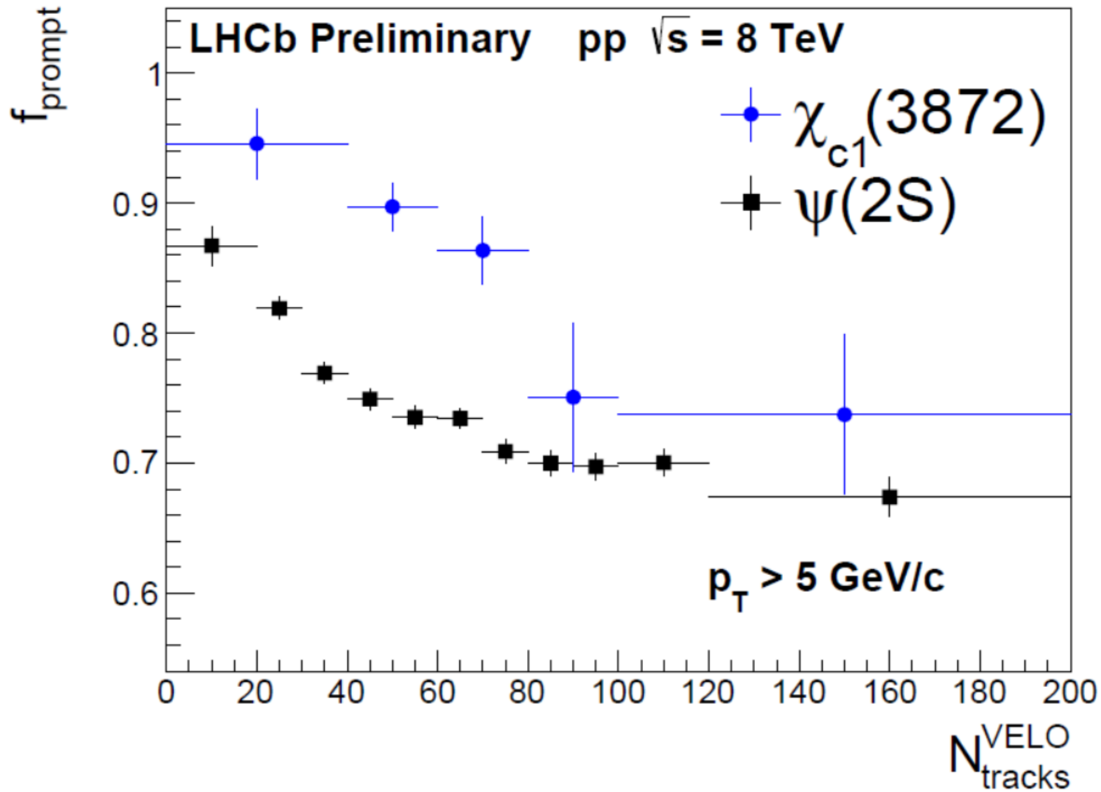
- **Large efficiency ratio due to a difference in energy release**

$$\varepsilon^{\mathrm{reco}}_{\psi(2S)}/\varepsilon^{\mathrm{reco}}_{\chi_{c1}(3872)} = 0.62$$

- Kinematic distribution from measured **ψ(2S) distributions at 7 and 13 TeV, reweighted for $\chi_{c1}(3872)$ using the scaling factor**

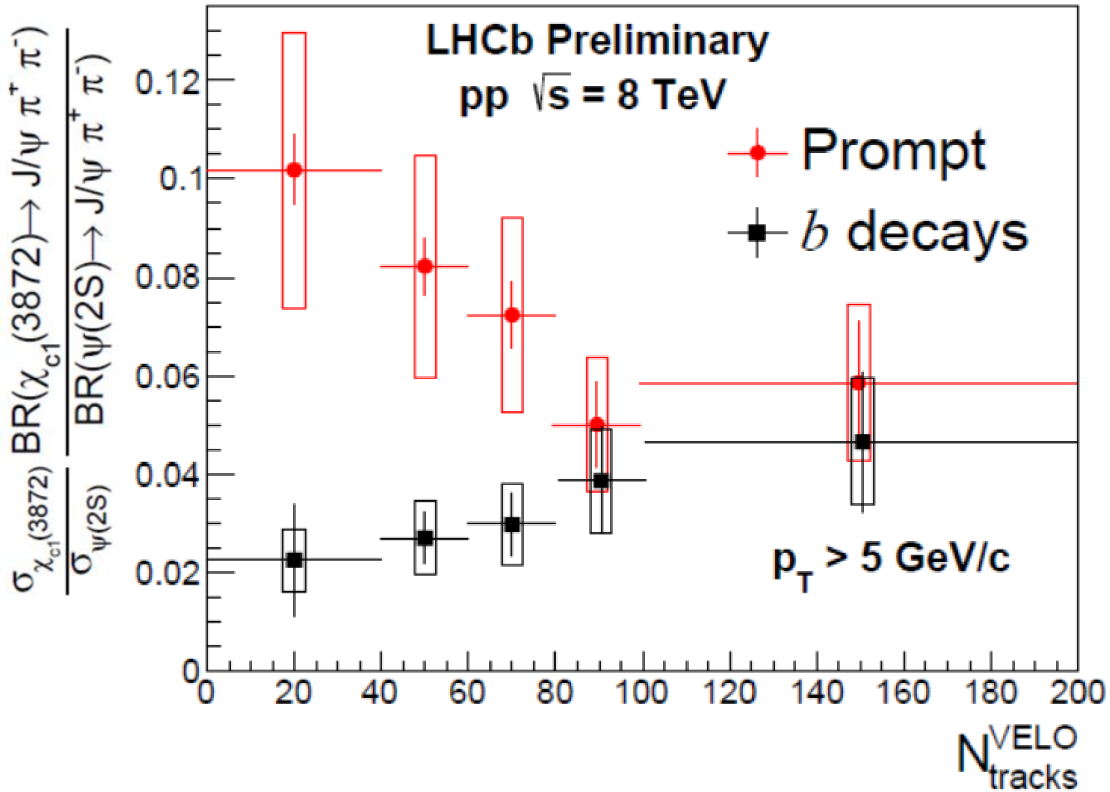
$$p_{\mathrm{T}} \rightarrow m_{\mathrm{T}} = \sqrt{p_{\mathrm{T}}^2 + (M^2_{\chi_{c1}(3872)} - M^2_{\psi(2S)})}$$

- The prompt fraction decreases as the event activity increases, for both $\chi_{c1}(3872)$ and $\psi(2S)$



- Possible reasons:
  - Larger average multiplicity of events with $b\bar{b}$ due to their fragmentation into hadrons and subsequent decays → **larger b-decay component in events with high multiplicity**
  - Suppression of prompt $\chi_{c1}(3872)$ and $\psi(2S)$ production via interactions with other particles produced at the vertex → **reduced prompt production in high multiplicity events, production in b decays not affected**

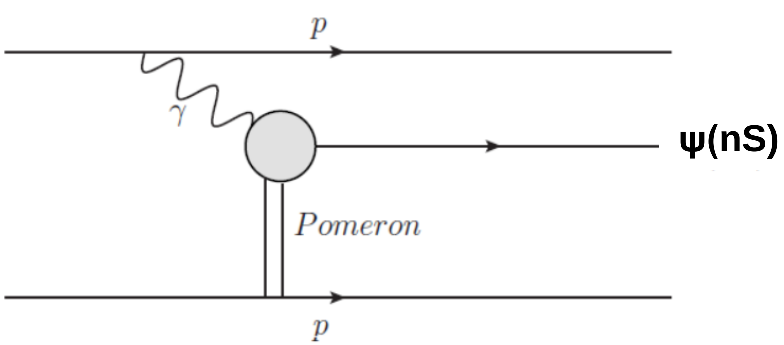
- **Ratio of cross-sections, $\chi_{c1}(3872)$ and $\psi(2S)$**, for prompt and b-decay production



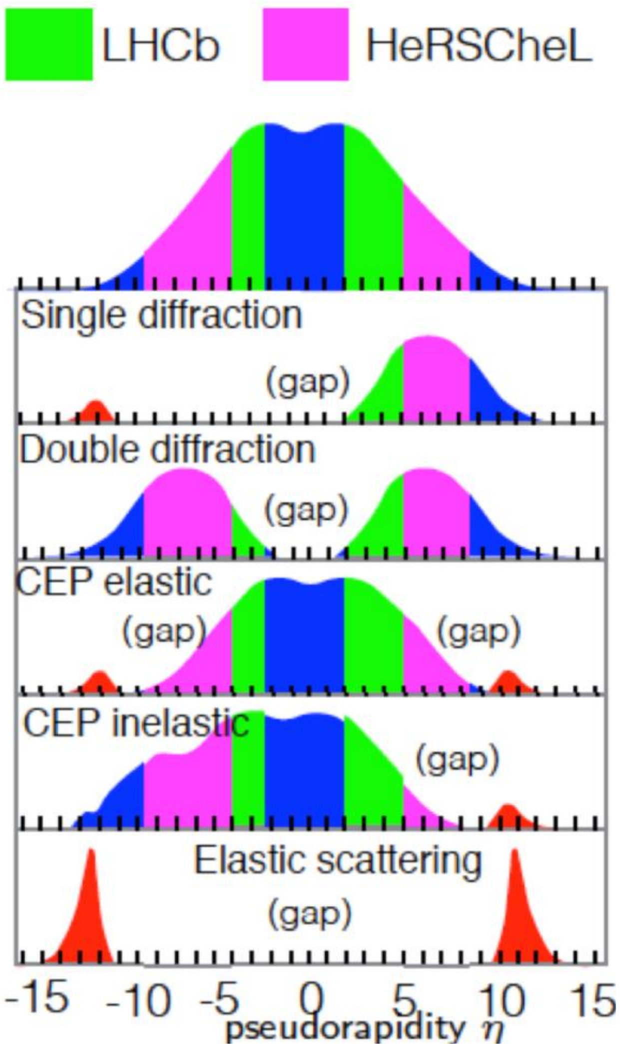
- Evidence for **relative $\chi_{c1}(3872)$ suppression for high-multiplicity events**
- Expected in a **scenario of interactions with co-moving hadrons** dissociating large weakly bound $\chi_{c1}(3872)$ against compact $\psi(2S)$
- Cross-check: production in b-decays

Central Exclusive Production of HF

- **QCD tests with clean theoretical interpretation**
- Only **CS production**
- Sensitivity with cross-sections in the LHCb coverage down to x ~ 1.5 x 10^{-5}



- **CEP: large rapidity gap**



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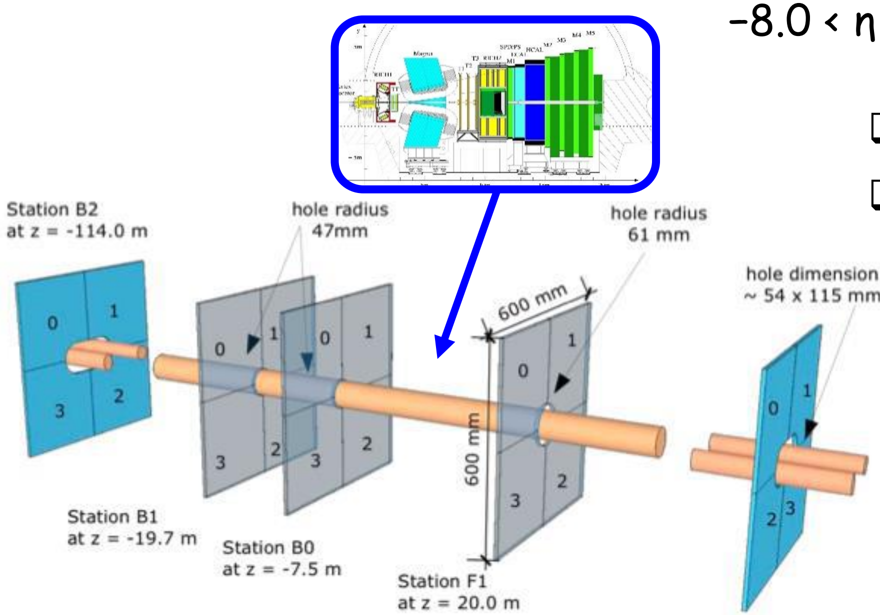
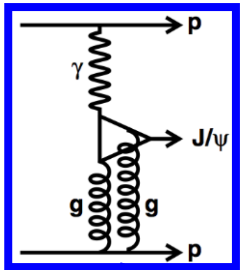
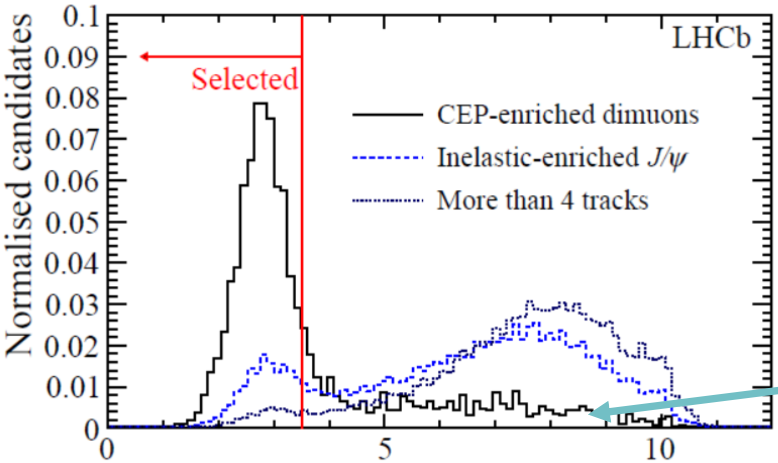
$\sqrt{s}$=13 TeV, ∫Ldt ~0.2 fb^{-1}

- **Herschel detector** increases rapidity gap in forward region
  $-8.0 < \eta < -1.5$, $5.0 < \eta < 8.0$

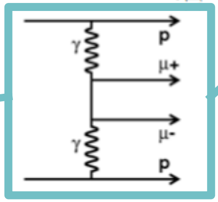


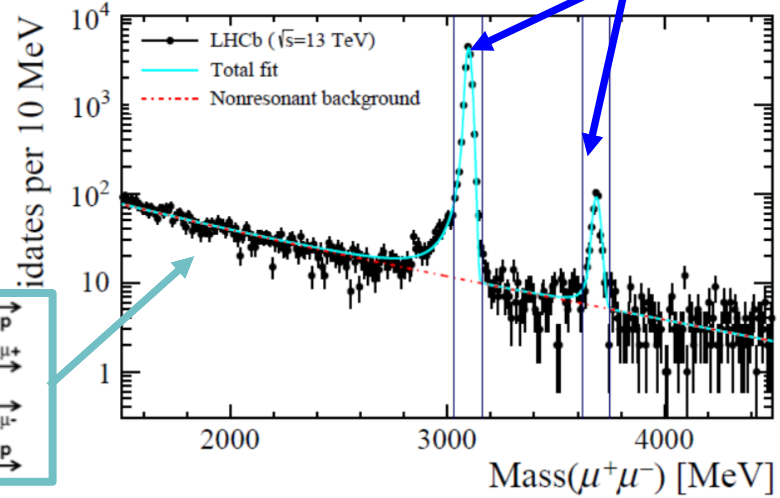
- Dedicated CEP trigger
- **Exclusivity**: precisely two forward muons; no backward tracks; no activity in SPD (< 10 hits). Quantify with p_T spectrum.





Sum of Herschel deposits in quadrature



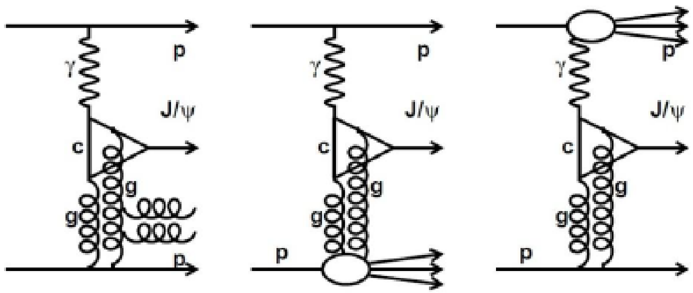


Signal shape

- Estimated from Superchic using $\exp(-b\, p_T^2)$
- Slope b estimated from HERA data, agreement to the fit of LHCb data

Inelastic backgrounds

- One/two protons dissociate(s) or additional gluon radiations. Extra particles are undetected.
- P_T shape estimated from data, cross checked with PYTHIA, LPAIR



Feed-down

$\psi(2S) \to J/\psi\pi\pi$: $2.5 \pm 0.2\%$
$\chi_c \to J/\psi\gamma$ $7.6 \pm 0.9\%$
$X(3872) \to \psi(2S)\gamma$ $2.0 \pm 2.0\%$

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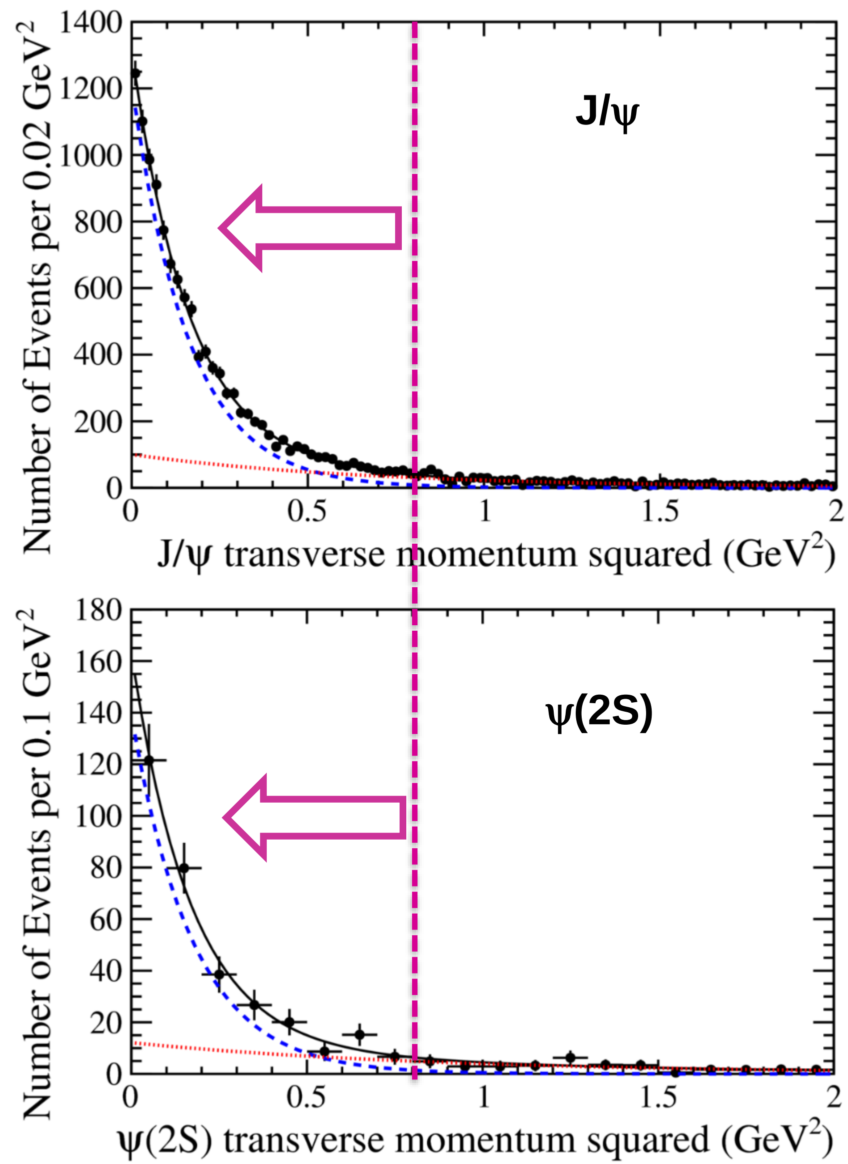
$\sqrt{s}$=13 TeV, $\int L dt$ ~0.2 fb^{-1}



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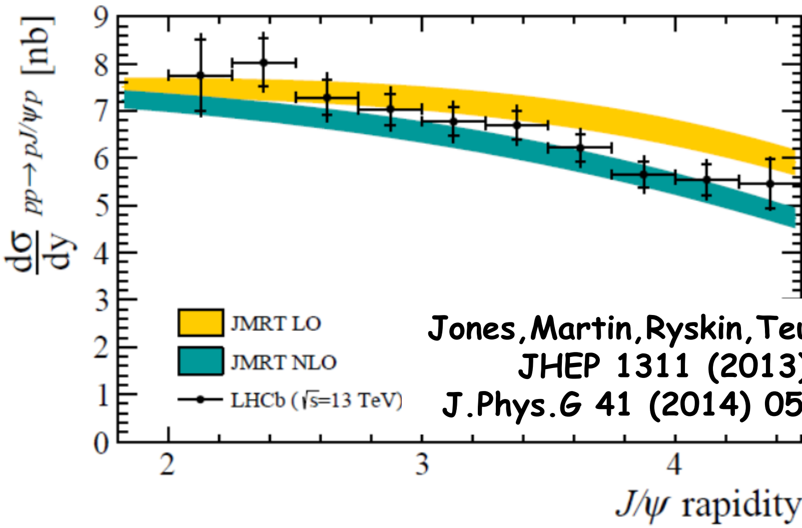
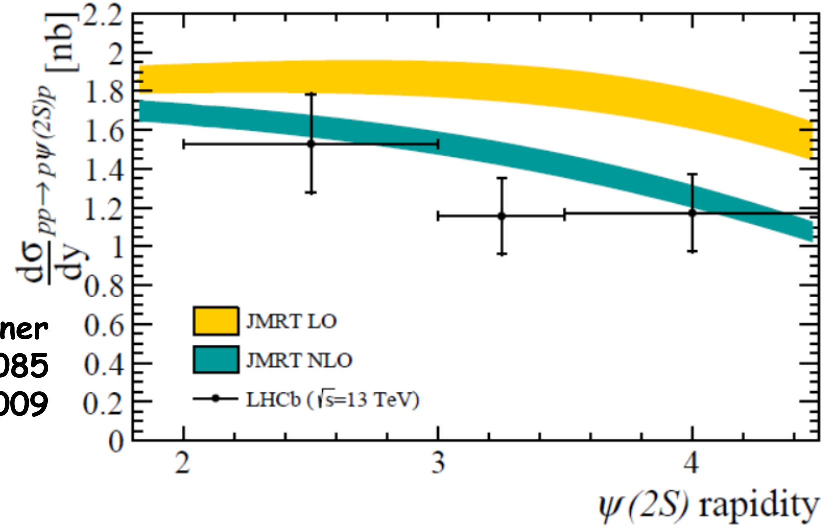
$\sqrt{s}$=13 TeV, $\int L dt$ ~0.2 fb^{-1}

- **Differential cross-sections** compared to theory predictions





Jones, Martin, Ryskin, Teubner
JHEP 1311 (2013) 085
J.Phys.G 41 (2014) 055009

- **Integrated cross-sections** times branching fractions

$$\sigma_{J/\psi\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 407 \pm 8 \pm 24 \pm 16 \text{ pb}$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 9.4 \pm 0.9 \pm 0.6 \pm 0.4 \text{ pb}$$

- **Good agreement with NLO predictions**
- Confirms a hint of NLO importance from the analysis at 7 TeV

Photo-production cross-section

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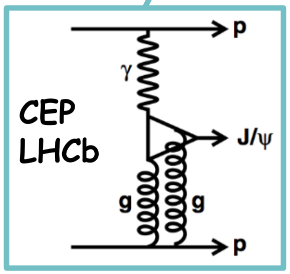
$\sqrt{s}$=13 TeV, $\int Ldt$ ~0.2 fb^{-1}

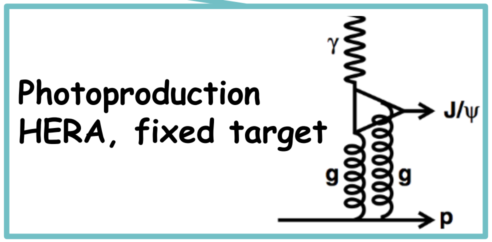
- The cross-section for the CEP of vector mesons in pp collisions is related to the **photo-production cross-section**:

$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{dn}{dk_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_-\frac{dn}{dk_-}\sigma_{\gamma p\to\psi p}(W_-)$$



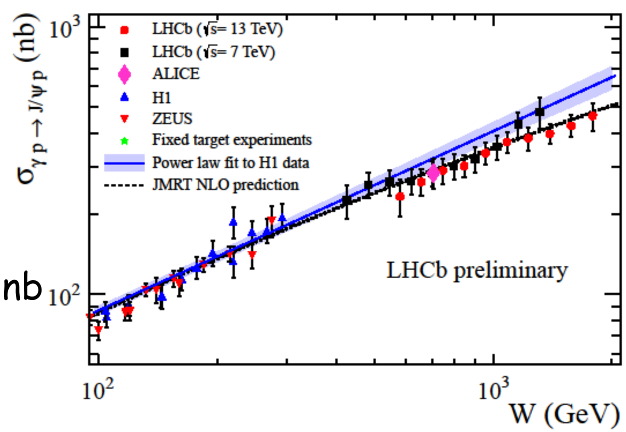
Gap survival

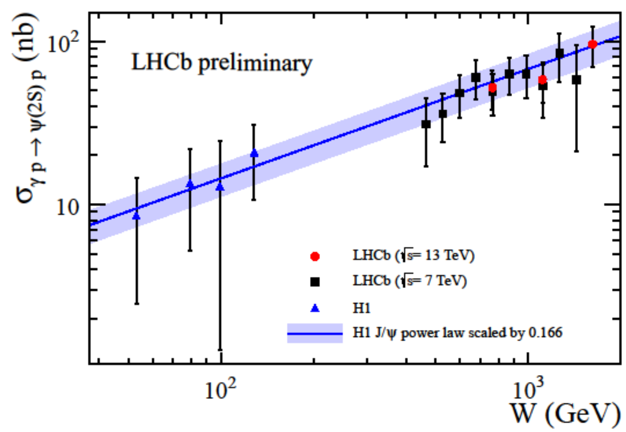
Photon flux



Jones, Martin, Ryskin, Teubner, JHEP 1311 (2013) 085, J.Phys.G 41 (2014) 055009, and update

- Compilation of photo-production cross-section measurements
- H1 measured power-law: $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\ GeV)^{0.67}$ nb

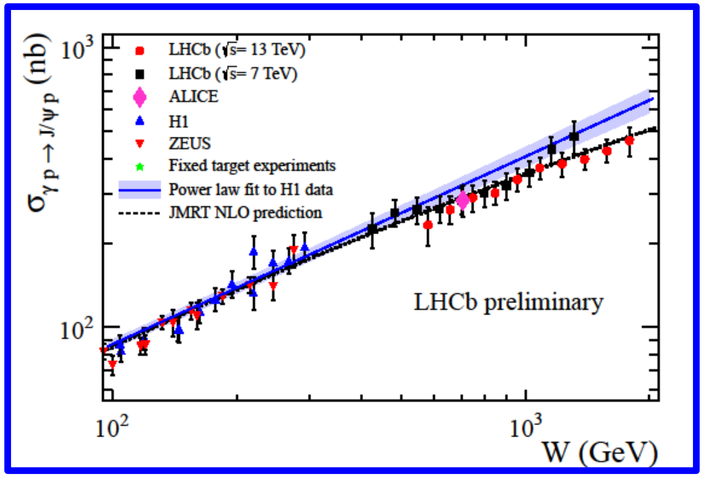


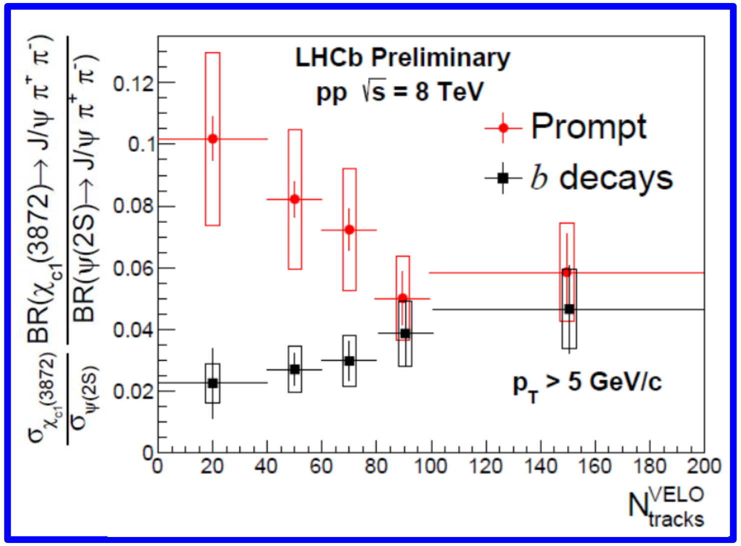


- Good agreement between LHCb results at 7 and 13 TeV
- J/ψ photo-production cross-section: **deviation from a pure power-law extrapolation of HERA data; agreement to theory prediction**

Summary

- Thanks to excellent LHC and LHCb operation, **many important results on charmonium production**
- The ultimate dream is a comprehensive model capable to provide a simultaneous description of observables for all measured states and production sources in the entire p_T range





- **Theory/experiment** agreement made great progress since Tevatron days
- Prompt charmonium production still puzzle
- Specific processes (e.g. CEP) allow a clean interpretation

- Clear need to improve **precision** for both theory AND experiment
- Charmonium production in **heavy ion collisions** remain largely unexplored.
- Still much to be leant at LHC